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Dr. Peter Lent
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DOCUMENTATION OF THREE SIMULATION MODELS DEVELOPED FOR THE SAVAL RANCH RESEARCH AND EVALUATION PROJECT

by

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United States Department of the Interior

BUREAU OF LAND MANAGEMENT
Nevada State Office
300 Booth Street
Reno, Nevada 89520

IN REPLY
REFER TO:

November 16, 1984.

MEMORANDUM

To: Recipient

From: Peter Lent, Saval Project Manager

Subject: Documentation for Saval Project Simulation Models

Enclosed is the final report from ESSA providing documentation for three models in addition to the riparian zone one documented in the previously distributed report.

Anyone wishing a diskette with the two Apple programs should let me know.

P. Lent

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I. The Saval Ranch Integration Model

1. INTRODUCTION

The Saval Ranch Integrated Model was developed over the period from November, 1981 to January, 1982. Two workshops were held, with a total of forty participants, who provided the insight and data necessary to construct and refine the model.

All of the functional relationships and assumptions of the model are described in a detailed report (Sonntag, et al., 1981), which should be consulted when reading the following documentation.*

The model is designed for the MTS operating system and the SIMCON simulation language. MTS is available on computers at several universities; SIMCON may be purchased from the University of British Columbia, Institute of Animal Resource Ecology. The model is currently stored on tape at Wayne State University. Persons or institutions interested in using the complete model would need to obtain permission from the Bureau of Land Management, and liaise with ESSA Ltd. regarding transfer of the model from Wayne State. For those persons interested in modelling particular components of the system (e.g., hydrology, sage grouse population dynamics), the program listings presented herein contain some useful techniques and structures.

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*All references to figures and tables in the text of Section I refer to Sonntag, et al., 1982.

2. VARIABLE DICTIONARY

The following pages describe all constants and variables used in the integrated model. For arrays, these indices are used to explain frequently used array dimensions:

ctype - cattle type:
1 = cows
2 = calves
3 = yearlings

ncover - cover types. Two breakdowns are used:
(1) grass, shrub, tree, canopy and ground
(2) shrub, bare, grass, rock and litter

ngrt - grouped range sites:
1 = claypan
2 = loamy
3 = riparian

nlyr - soil layers:
1 = 0 - 10"
2 = 10 - 20"
3 = 20 - 40"

nman - type of vegetation manipulation:
1 = ploughing
2 = burning
3 = spraying
4 = mining

nmead - meadows:
1 = Tremenan
2 = Gance
3 = Haystack

npas - pastures:
1 = West Darling
2 = East Darling
3 = Lower Mahala
4 = Middle Mahala
5 = Upper Mahala
6 = Lower Sheep Creek
7 = Upper Sheep Creek
8 = East Independence North
9 = East Independence South

nper - deer migration phases:
1 = March 15 - May 15
2 = May 15 - June 15
3 = June 15 - November 1

nrt - range sites:
1 = loamy bottom
2 = wet meadow
3 = claypan 10 - 12"
4 = loamy 8 - 10"
5 = claypan 12 - 16"
6 = loamy 10 - 12"
7 = loamy slope 10 - 14"
8 = loamy slope 14 - 18"
9 = aspen woodland
10 = slope 12 - 14"

nst - identified sage grouse strutting grounds (see Figure 6.5, page 104 of Sonntag, et al., 1982)

nveg - vegetation types:
1 = bitterbrush
2 = sagebrush
3 = other brush
4 = forbs
5 = perennial grasses (decreasers)
6 = perennial grasses (increasers)
7 = cheatgrass

stream - creek 3:
1 = Gance
2 = Mahala
3 = North Fork

weeks - the period from March 15 to November 30 corresponds to weeks 1 - 38. December 1 to March 14 is "week" 39.

2. VARIABLE DICTIONARY

2.1 Vegetation Submodel

VARIABLE	DEFINITION
ACNEW(npas,nrt,nlyr)	available water capacity by soil layer by range site by pasture
AMEAD(3)	area of hay meadows (a.)
ARET	area returned to pasture from seeding reserve (a.)
AWC(nrt,npas)	old available water capacities by range site by soil layer
CVPX(2)	week (for slp function CVPY)
CVPY(2)	cheatgrass % protein = f (week)
CWST	cow wastage as fraction of amount consumed
DPB	net growth rate in above ground biomass (including grazing)
DROOT	growth in root biomass (lbs/a.)
ER(nrt)	erosion index
GMAX(nveg)	maximum plant growth rate/week
GMRED(npas,nrt,nveg)	fractional growth reduction due to soil moisture (0-1)
GPCWT(npas,nveg)	% of each plant type on each pasture (by weight)
GPLANT(npas,nrt,nveg)	weekly growth rate in above ground biomass pregrazing
GSOXM(1,5)	claypan % moisture (SLP function for GSOY)
GSOXM(2,5)	loamy % moisture (SLP function for GSOY)
GSOXM(3,5)	riparian % moisture (SLP function for GSOY)
GSOY(5)	growth rate reduction = F (soil moisture)
GTEMPX(3)	temperature (degrees F.) (SLP function for GTEMPY)
GTEMPY(3)	growth rate reduction = F (temperature)

VARIABLE	DEFINITION
GTPROD(npas)	total production of forbs and perennial grasses by pasture at flowering time
HAYOP(nmead)	level of hay operations; 1 = poor irrigation, 2 = good irrigation, 3 = fertilization
HAYP(nmead)	hay production by meadow (1 = Tremenan, 2 = Gance, 3 = Haystack)
HAYY(3,5)	SLP function for hay production = F (level of hay operations (HAYOP, 1st subscript) and streamflow (HX, 2nd subscript))
HMMR	% moisture causing 100% mortality of shrubs
HX(5)	SLP function for streamflow (a. - ft./a. of meadow)
HY(5)	temporary copy of one row of HAYY
IFDATE	week of flowering
ILUMP	switch to lump old range sites into new ones
IOC(npas)	array used to skip over pastures (skip if IOC(npas) = 0)
IVM	switch for vegetation manipulation; none if = 0
NEWRS(ngrt,5)	array for grouping of old range sites listed in columns into new range sites (rows)
NPAS	# pastures
NRT	# range site types
PAST(npast)	pasture areas (a.)
PC(npas,nrt,nveg)	% cover of each vegetation type
PCMAX(ngrt,ncover1)	% of cover types (1) for each grouped range site
PCMAX2(ngrt,ncover2)	% of cover types (2) for each grouped range site
PCWT(npas,nrt,nvag)	% of each plant type by range site by pasture (by weight)
PLNTMX(nveg)	maximum vegetation biomass (lbs/a.)

VARIABLE	DEFINITION
PMR	weekly mortality rate of vegetation
PMX(2)	SLP function with PMY; vegetation weekly growth rate
PMY(2)	SLP function % mortality of vegetation = F (growth rate)
PREM	fraction of range site removed by vegetation manipulations
PRTS	fraction of root biomass sent to shoots/week (before flowering)
PSTR	fraction of shoot biomass sent to roots (after flowering)
PTOT	total weight of all plants on one range site in one pasture
PVPX(2)	SLP function with PVPY; week
PVPY(2)	SLP function; % protein of grasses and forbs (= F (week))
PWS(nveg)	plant winter survival
PWTMAX(ngrt,2)	maximum % by weight (1) and % cover (2) of shrubs and grasses
RA(npas,nrt,nveg)	biomass (lbs/a.) of each plant type
REQGA	weekly growth rate required before flowering (if less, get from roots)
REQGB	weekly growth rate required after flowering (if more, pass to roots)
RLP	ratio of % cover of grass and litter to % cover of grass
ROOT(npas,nrt,nveg)	root biomass (for all plant types but cheatgrass) by pasture and range site
ROOTMX(nveg)	maximum root storage (lbs/a.)
RPB	(roots/above ground) at start
RWS	survival of root potential biomass over winter
SHKILL(nman)	fraction of shrubs killed by type of manipulation

VARIABLE	DEFINITION
SPB	exponent for setting initial plant biomass
SPBEXP	exponent for setting initial plant biomass
SVPX(all)	SLP function with SVPY; week
SVPY(all)	% protein of shrubs (= F (week))
THAYP	total hay production
TOTPCT	% canopy cover plus % ground cover
TPROD(npas,nveg)	total plant production
TRED	fractional growth reduction due to temperature
VMANIP(npas,nrt,nman)	# acres manipulated in given pasture and range site
VP(nveg)	% protein content of each plant type
VSEED(nveg)	plant biomass after seeding
WMAX	soil moisture (%) in wettest soil layer available to plant
WPA(1-3)	water/acre for 3 hay meadows

2.2 Hydrology Submodel

VARIABLE	DEFINITION
APAR	used in calculating curve number
ARGNC(nrt)	areas of range types in Gance basin
ARMAH(nrt)	areas of range types in Mahala basin
AWCNEW(npas,nrt,nlyr)	available water capacity in inches
BETOT	total bank erosion (tons)
BPAR	used in calculating curve number
BSTAB	% stable streambank
BSTB1	parameter for calculating bank stability
BSTB2	parameter for calculating bank stability
CATFAC	coefficient relating cattle to bank erosion
CFAC	function of ground cover used in erosion
CN	SCS curve number
CNA(ngrt)	parameters for calculating curve number
CNB(ngrt)	parameters for calculating curve number
CUFS	converts inch. acres/day to cubic feet/sec.
DMTEMP	daily mean temperature (°F)
DPRECT(npas)	snowmelt and precipitation in inches
ER(nrt)	erodability
ETPOT	potential evapotranspiration in inches
ETPLNT	evapotranspiration by plants
ETSOIL	evaporation from soil in inches
FLFUDG	--not used--
FLGNC	flow in Gance Creek in cubic feet/sec.
FLMAH	flow in Mahala Creek in cubic feet/sec.

VARIABLE	DEFINITION
FREZDP(npas,nrt)	depth of frozen soil in inches
FTOT(stream)	total flow to date in current year by stream
FWTOT(stream)	weekly total flow in each stream
LUPTR(npas)	pointer from pasture to hydrologic soil group
NDAYS	# of days in current time step
NFFLOW(weeks)	flow in North Fork by weeks
OCN	curve number for area outside Saval
ORUN	runoff from area outside Saval
OS	retention parameter for area outside Saval
PACAN	percent active canopy
PMECH	factor related to soil conservation
PMULT	multiplier for rain on USFS lands
PREC(365)	daily rainfall on BLM lands (inches)
PRECIP(npas)	--not used--
RADLAN	solar radiation in langleys
RFAC	parameter related to storm intensity
RFUDG	--not used--
RUNOFF(npas,nrt)	water runoff in each spatial unit
S	soil retention parameter
SEDDEL	sediment delivery coefficient
SMAX	maximum soil retention parameter
SMELT	snowmelt in inches
SNOPAC(npas,nrt)	snow storage in inches of water
SO(npas,nrt,3)	weekly mean soil water as % AWC
SOFDG	--not used--
SOILOF(npas,nrt)	erosion in tons/acre

VARIABLE	DEFINITION
SOWAT(npas,nrt,3)	inches of water in each horizon
TMAXL(365)	daily maximum temperature on BLM lands (°F)
TMAX(npas)	weekly mean maximum temperature
TMINL(365)	daily minimum temperature on BLM lands (°F)
TMULT	multiplier for temperature on USFS lands
UEGNC	upland erosion into Gance (tons)
UEMAH	upland erosion into Mahala (tons)
WATRES(nlyr)	depth of soil horizons in inches
WATIN	infiltration in inches
WATQAL	daily water quality
WINDAY	# of days in winter time step
WQUAL	weekly mean water quality
WTWOOD	weighted % woody cover in riparian
XLS(nrt)	length slope parameter used in erosion

2.3 Cattle and Economics Submodel

VARIABLE	DEFINITION
BEAT(ctype)	weekly biomass intake of each cattle type
CALF	# calves born before 1st year simulation
CALFS	# calves sold in fall
CALFW	calf weight on April 15 (lbs)
CE(npas,ngrt,nveg)	initial consumption (lbs/acre)
CLFB	# calves bought in spring
CMIN(2)	target spring weights: cows, calves
COSTS	total ranch costs ($)
COW(ctype)	initial # cattle
COWB	# cows bought in spring
COWMAX	target # cows on Saval Ranch
COWS	# cows sold in fall
COWW(ctype)	initial cattle weights (lbs)
CVA	county value added (Equation 5.10)
DAW	$/acre to improve irrigation
DBH	$/ton to buy hay
DGH	$/ton to grow hay
DPW	# days per week
DPWN	# days in winter period
DSH	$/ton revenue for sold hay
FC	fixed ranch costs
GVO	gross value of county output (Equation 5.8)
HAYB	tons hay bought
HAYR(ctype)	lbs hay required for each cattle type over winter

VARIABLE	DEFINITION
HAYS	tons hay sold
HPP(3)	slope of winter growth versus intake (Figure 5.8)
IAHB	hay buying switch: = 1, needed hay bought
IAHS	hay selling switch: = 1, excess hay sold
IENR	week cattle taken off range
IGR(npas)	slot of pasture before simulation begins
IGRT	initial # weeks to date on pasture NPAST
IPAST(npas)	--not used--
IPCNT(ipas)	# years pasture has been in present rotation slot
IPREF(nveg)	plant type preferences
IPTO(npas)	transition array for rotation (Table 5.2a)
IPW(npas)	# weeks cattle graze each pasture
IPYN(npas)	# years pasture is kept in same rotation slot
ISTOP	switch for computing fall and winter; = 0 fall/winter not done
ISTR	week that cattle put on range
IUSE	pasture currently being used
IWM	if = 9, feed only "near" water, = 10, feed "distant" too
NPMAX	# pastures grazed by cattle
PAS	proportion cows sold in fall
PCALF	% calving
PCS	proportion calves sold in fall
PPCLF	$/lb of calf bought/sold
PPCOW	$/lb of cow bought/sold
PPYR	$/lb of yearling bought/sold
RA(npas,ngrt,9-10)	proportion of range sites near water, distant from water (respectively)

VARIABLE	DEFINITION
REV	total ranch revenues ($)
RNA	ranch value added (Equation 5.9)
RNP	ranch purchases (Equation 5.7)
SLI	slope of intake versus weight relationship (Figure 5.3)
SLTDN(nveg)	slope of proportion TDN versus proportion protein (Figure 5.5)
TGWA	counter for acres added to "near" water class
TGWAO	counter for acres added to "near" water class
THAYG	total lbs hay grown
THAYR	total hay required over winter period
TREQ(ctype)	total weekly food requirements for each cattle type (lbs)
TTREQ	total weekly food requirements for entire herd
VCC	per cattle variable costs
WGAIN(ctype)	weekly weight change
WGAR(8,6)	input matrix for Figure 5.6. The model interpolates down column 1 (cattle weight), then interpolates across to get daily intake (lbs TDN)
XCLF(6)	X-array for calving function (Figure 5.7)
XM1	economic multiplier (Equation 5.8)
XM2	economic multiplier (Equation 5.10)
XM3	economic multiplier (Equation 5.9)
XWNG(all)	X-array for winter weight gain (Figure 5.8)
YCLF(all)	Y-array for calving function (Figure 5.7)
YEARS	# yearlings sold in fall
YEARW	weight yearlings bought
YII	Y intercept of intake versus weight relationship (Figure 5.3)

VARIABLE	DEFINITION
YRB	# yearlings bought in spring
YTDN(nveg)	Y intercept of proportion TDN versus proportion protein (Figure 5.5)
YWG(5)	input Y-array for weight gain (Figure 5.6)
YWNG(all)	Y-array for winter weight gain (Figure 5.8)

2.4 Wildlife Submodel

VARIABLE	DEFINITION
AHEN(nst)	initial condition; adult hens on strutting grounds for 5 identified populations
AMALE(nst)	initial condition; adult males on strutting grounds for 5 identified populations
ANEED	kcal * 10 * 3 needed/adult/week
ANESMN	minimum adult nesting success if forbs density too low
ANX(3)	forb and grass biomass (X-axis of Figure 6.6)
ANY(3)	adult nesting success as function of average density of forbs and grasses (Y-axis of Figure 6.6)
CAL(nveg,12)	nutritional value for each plant type by month (10^3 * kcal/lb)
CHENMN	minimum chicks/nest
CHX(3)	chicks/hen (X-axis of Figure 6.7)
CHY(3)	number of chicks per hen as function of average forbs and grasses density (Y-axis of Figure 6.7)
CMALE	proportion of sage grouse that are male (in fall)
DAYH	# days/hunter/year
DENERF	initial condition - kcal 10^3 ingested by fawn deer in previous year
DENERA	initial condition - kcal 10^3 ingested by adult deer in previous year
DFEM	initial number of female adult deer
DINGW(2)	lbs/week ingested by 1) fawn; 2) adult deer
DMALE	initial number of male adult deer
FAWN	initial number of fawns
FK	half saturation parameter in extra mortality function applied to fawn deer

VARIABLE	DEFINITION
FLEAVE(nveg)	amount of forage not eaten
FNEED	kcal * 10 * 3 needed/fawn/week
FPERC	proportion of fawns that are male
FRAC	fraction of deer population overwintering east of Saval project
HFRAC	proportion of game management unit covered by Saval project area
HHX(3)	density of bucks on range for SLP function (X-axis of Figure 6.4)
HHY(3)	deer hunting success per unit of effort - hunter days (Y-axis of Figure 6.4)
ISTRUT(nst)	pastures containing sage grouse strutting grounds
NPASD(nper,npas)	pastures used by deer in each of 3 periods
NPERP(3)	number of pastures utilized by deer in 3 period
NPERT(3)	number of range sites used by deer in 3 periods
NTYPE(nper,nrt)	range sites used by deer in each period
PERIN(all,all,all)	initial condition - proportion of each plant type in deer diet by pasture and range type
PERMIT	# deer hunting permits in game management unit
PREF(nveg,12)	monthly preference parameters for each type of vegetation
RRA(npas,ngrt,nveg)	dummy variable to reflect density of plants after removing cattle grazing - otherwise same as RA
SAGEG	total number of sage grouse on Saval ranch March 15
SHUNT	proportion of sage grouse population removed by hunting
SK	half saturation parameter in extra mortality function applied to sage grouse

VARIABLE	DEFINITION
TOTHEN	total number of sage grouse hens March 15
TOTMAL	total number of male sage grouse March 15
WE(npas,ngrt,nveg)	pounds/acre of each plant type ingested by deer each week
WHENS	overwinter survival rate for hens
WMALES	overwinter survival rate for males
XFAW(all)	X-axis of Figure 6.3
XFEM(all)	X-axis of Figure 6.2 (females health index)
XFNY(all)	X-axis of Figure 6.2 (fawns health index)
XHFAC(4)	shrub cover (X-axis of Figure 6.9)
XHSUR(3)	forb and grass biomass (X-axis of Figure 6.8)
XMALED(all)	X-axis of Figure 6.2 (males health index)
XMSUR(all)	shrub cover (X-axis of Figure 6.10)
YFAW(all)	# fawns/female as function of health index (Y-axis of Figure 6.3)
YFEM(all)	female winter survival as function of health index (Y-axis of Figure 6.2)
YFNY(all)	fawn winter survival as function of health index (Y-axis of Figure 6.2)
YHEN(nst)	initial conditions yearling hens on 5 identified populations
YHFAC(all)	hen survival modification factor as function of shrub cover (Y-axis of Figure 6.9)
YHSUR(all)	hen survival over March 15 to September 30 as function of forbs and grasses (Y-axis of Figure 6.8)
YMALED(all)	male winter survival as function of health index (Y-axis of Figure 6.2)
YMALE(all)	initial conditions yearling males on 5 identified populations
YMSUR(all)	male survival March 15 to September 30 as function of % shrub cover (Y-axis of Figure 6.10)

VARIABLE	DEFINITION
YNESMN	minimum yearling nesting success if forbs density too low
YNX(all)	forb and grass biomass (X-axis of Figure 6.6)
YNY(all)	yearling nesting success as function of forbs and grasses average density (Y-axis of Figure 6.6)

3. PROGRAM LISTINGS

The computer program listings are in three sections:

3.1) FORTRAN source code;

3.2) data files; and

3.3) common block.

The model is structured hierarchically (Figure 1), and runs under a simulation language called SIMCON (Hilborn, 1973). When the model is run, SIMCON first calls an initialization subroutine (UINIT) to read in the common block and allocate storage (performed by the subroutine CMREAD) and store the variables' initial values (performed by the subroutine DFAULT). The main line subroutine UMODEL is called during each time step, which in turn calls each of the submodel subroutines. Table 1 shows the relationship between subroutines, data files and common blocks.

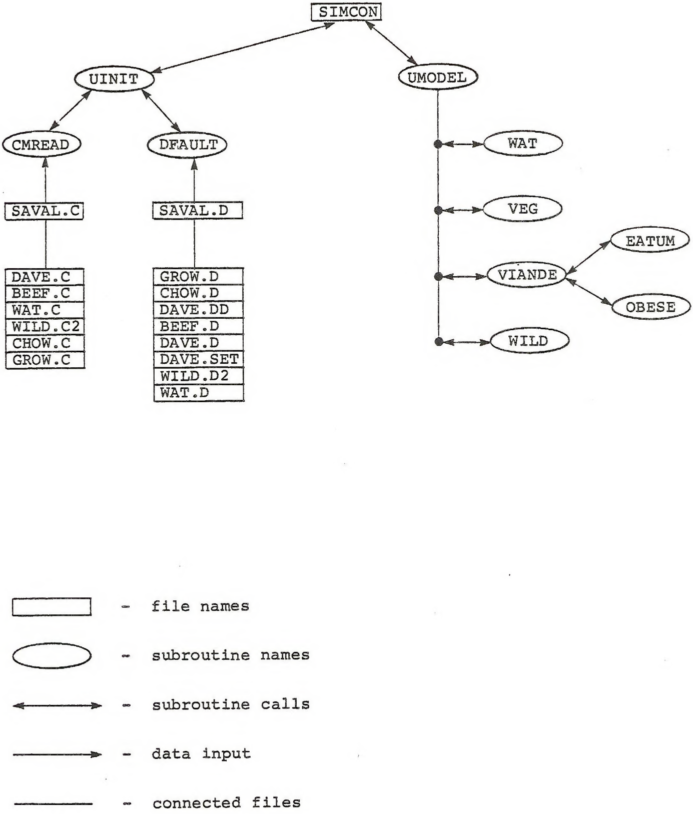

Figure 1: Structure of the Saval Ranch integrated model. Files and subroutines are listed in the order they appear in the program.

Table 1: Data files and common block files associated with each submodel.

SUBMODELS	SUBROUTINE NAMES	DATA FILES	COMMON BLOCK FILES
Mainline	UMODEL	SAVAL.D	SAVAL.C
Vegetation	VEG	DAVE.D DAVE.DD	DAVE.C
Hydrology	WAT	WAT.D	WAT.C
Cattle and Economics	VIANDE EATUM OBESE	BEEF.D CHOW.D GROW.D	BEEF.C CHOW.C GROW.C
Wildlife	WILD	WILD.D2	WILD.C2

3.1 FORTRAN SOURCE CODE

INITIALIZATION ROUTINE

This routine reads in the common block for all FORTRAN subroutines, and initializes all variables to the values listed in the data files.

```
      SUBROUTINE UINIT
      CALL CMREAD('SAVAL.C ')
      CALL DFAULT('1=SAVAL.D ')
      RETURN
      END
```

MAINLINE SUBROUTINE

This subroutine is called every time step (week). It then calls each of the other subroutines in the order shown.

```
      SUBROUTINE UMODEL(ITIME)
$CONTINUE WITH SAVAL.C RETURN
      IF(ITIME.GT.1) GO TO 300
      IF(IMUNCH.LT.2) GO TO 300
      TPREF=0.
      DO 900 IR=1,3
      DO 900 IF=1,7
      DO 900 IW=1,2
      TPREF=TPREF+FPREF(IF)*WPREF(IW)*RPREF(IR)
 900  CONTINUE
      DO 950 IR=1,3
      DO 950 IF=1,7
      DO 950 IW=1,2
      PREFF(IF,IR,IW)=(FPREF(IF)*WPREF(IW)*RPREF(IR))/TPREF
 950  CONTINUE
 300  CONTINUE
      IF(ITIME.EQ.1)IWEEK=0
      IF(ITIME.EQ.1.AND.ILUMP.EQ.1)CALL LUMP
      IWEEK=IWEEK+1
      IF(IWEEK.EQ.39)IWEEK=1
      IMONTH=(IWEEK+1)/4+1
C     WRITE(3,100) IWEEK
  100 FORMAT(I3)
      IF(IWAT.GT.0)CALL WAT(ITIME)
C     WRITE(3,100) IWEEK
      IF(IVEG.GT.0)CALL VEG(ITIME)
C     WRITE(3,100) IWEEK
      IF(IBEEF.GT.0)CALL VIANDE
C     WRITE(3,100) IWEEK
      IF(IWILD.GT.0)CALL WILD
C     WRITE(3,100) IWEEK
      RETURN
```

```
     END
$CONTINUE WITH VEG.S RETURN
$CONTINUE WITH BEEF.S RETURN
$CONTINUE WITH WAT.S RETURN
$CONTINUE WITH WILD.S2 RETURN
$CONTINUE WITH CHOW.S RETURN
$CONTINUE WITH GROW.S RETURN
```

VEGETATION SUBMODEL

This submodel is described in section 3 of the report.

```
     SUBROUTINE VEG(ITIME)
$CONTINUE WITH SAVAL.C RETURN
     IF(ITIME.NE.1)GO TO 18
     IF(ILUMP.EQ.0)GO TO 5
     CALL LUMP
     GO TO 18
C
C CHANGE RA FROM TOTAL PRODN TO BIOMASS AT START
C OF SEASON.  SET INITIAL ROOT BIOMASS.
C
5    DO 10 I=1,NPAS
     DO 10 J=1,NRT
     DO 10 IP=1,7
        IF(RA(I,J,8).EQ.0)GO TO 10
        ROOT(I,J,IP)=0
        IF(IP.GT.6)GO TO 10
        ROOT(I,J,IP)=RPB*RA(I,J,IP)
10   CONTINUE
C
C IMPLEMENT ACTIONS
C
18      IF(IVM.EQ.0)GO TO 45
     DO 42 I=1,NPAS
     IF(IOC(I).EQ.0)GO TO 42
     DO 40 J=1,NRT
     DO 40 K=1,4
        IF(VMANIP(I,J,K).EQ.0)GO TO 40
           IF(K.EQ.1.AND.VMANIP(I,J,K).LE.0)GO TO 35
           PREM=VMANIP(I,J,K)/RA(I,J,8)
C
C SHRUB KILL FOR BURNING OR SPRAYING
C
           IF(K.EQ.4)GO TO 25
           DO 20 IP=1,3
     IF(K.GT.1)RA(I,J,IP)=RA(I,J,IP)*(1.-SHKILL(K)*PREM)
     IF(K.EQ.1)VSEED(IP)=RA(I,J,IP)*(1.-SHKILL(K)*PREM)
20         CONTINUE
C
C REMOVE LAND IF PLOUGHING/SEEDING OR MINING.
C KEEP TRACK OF AMT. OF LAND IN SEEEDING RESERVE.
C
25          IF(K.EQ.2.OR.K.EQ.3)GO TO 40
```

```
            IF(K.EQ.1)RA(I,J,14)=RA(I,J,8)*PREM
            RA(I,J,8)=RA(I,J,8)*(1.-PREM)
            GO TO 40
C
C ADD LAND BACK INTO RA IF SEEDING READY FOR GRAZING.
C USE WEIGHTED AVERAGE OF PLANT BIOMASSES, AND
C FIXED MID-SUMMER  BIOMASS IN SEEDED AREA.
C
35          DO 38 IP=1,7
               ARET=-1.*VMANIP(I,J,1)
      IF(RA(I,J,8).LE.0)GOTO 38
               RA(I,J,IP)=(RA(I,J,IP)*RA(I,J,8)+
     1           VSEED(IP)*ARET)/(RA(I,J,8)+ARET)
38          CONTINUE
            RA(I,J,14)=RA(I,J,14)-ARET
            RA(I,J,8)=RA(I,J,8)+ARET
40    CONTINUE
42    CONTINUE
C
C HAY PRODUCTION. K=PASTURE (TREM.,GANCE.,HAYSTACK)
C
45    IF(IWEEK.NE.20)GO TO 100
      THAYP=0.
      DO 60 K=1,3
         I=9+K
         DO 50 M=1,5
50       HY(M)=HAYY(HAYOP(K),M)
      IF(K.EQ.1)WPA(1)=FTOT(2)/AMEAD(1)
      IF(K.EQ.2)WPA(2)=FTOT(1)/AMEAD(2)
      IF(K.EQ.3)WPA(3)=FTOT(3)/AMEAD(3)
      HAYP(K)=SLP(WPA(K),HX,HY,5)*AMEAD(K)
      THAYP=THAYP+HAYP(K)
60    CONTINUE
C
C GROWTH AND MORTALITY OF MAJOR PLANT TYPES.
C TREAT CHEATGRASS,PERENNIAL GRASSES AND FORBS,SHRUBS
C AS THREE GROUPS.
C
100   DO 475 I=1,NPAS
       IF(IOC(I).EQ.0)GO TO 475
C
C IF SEED SET, TOTAL UP PASTURE FORAGE PRODN
C PERENNIAL GRASSES AND FORBS ONLY.
C
      IF(IWEEK.NE.IFDATE)GO TO 102
      GTPROD(I)=0
      DO 101 IP=4,6
101   GTPROD(I)=GTPROD(I)+TPROD(I,IP)
102       IF(IWEEK.NE.1)GO TO 105
          DO 103 IP=1,7
103       TPROD(I,IP)=0.
 105      TRED=SLP(TMAX(I),GTEMPX,GTEMPY,3)
          DO 450 J=1,NRT
             IF(RA(I,J,8).EQ.0)GO TO 450
C
C COPY MOISTURE X-AXIS APPROPRIATE TO RANGE TYPE
```

```
C FROM MASTER
         DO 110 K=1,5
110      GSOX(K)=GSOXM(J,K)
C
C COMPUTE TOTAL PLANT BIOMASS ON RANGE SITE.
C
         TOTPB(I,J)=0
         DO 115 IP=1,7
         TOTPB(I,J)=TOTPB(I,J)+RA(I,J,IP)
115      CONTINUE
            DO 400 IP=1,7
               IF(RA(I,J,IP).EQ.0)GO TO 400
               IF(IWEEK.EQ.38)GO TO 300
               WMAX=SO(I,J,1)
               WMIN=AMIN1(SO(I,J,1),SO(I,J,2),SO(I,J,3))
C CHEATGRASS - USES MOISTURE IS UPPER 10" ONLY
               IF(IP.EQ.7)GO TO 120
               IF(SO(I,J,2).GT.WMAX)WMAX=SO(I,J,2)
C GRASSES AND FORBS - USE MAX. OF MOISTURE IN 0-10" AND 10-20"
               IF(IP.GE.4.AND.IP.LE.6)GO TO 120
C SHRUBS - USE MAX. OF MOISTURE IN ALL 3 SOIL LAYERS
               IF(SO(I,J,3).GT.WMAX)WMAX=SO(I,J,3)
C
C COMPUTE POTENTIAL PLANT GROWTH RATE WITH NO COMPETITION
C
120         GMRED(I,J,IP)=SLP(WMAX,GSOX,GSOY,5)
               GPLANT(I,J,IP)=GMAX(IP)*TRED*GMRED(I,J,IP)
C
C RECOMPUTE PLANT GROWTH RATE TO ACCOUNT FOR COMPETITION.
C POTG=POTENTIAL GROWTH (LB/A)
C REDUCE PLANT GROWTH RATE IF NOT ENOUGH WATER TRANSPIRED,
C BUT LEAVE GROWTH RATE AS IS IF WATER SURPLUS.
C
               RQEVIN=RA(I,J,IP)*RQEVLB(IP)*0.000276
               AVEVIN=PEVAP(I,J)*RA(I,J,IP)/TOTPB(I,J)
               GCOMP(I,J,IP)=0.
               IF(RQEVIN.NE.0)GCOMP(I,J,IP)=AVEVIN/RQEVIN
               IF(AVEVIN.GE.RQEVIN)GO TO 140
               GPLANT(I,J,IP)=GPLANT(I,J,IP)*AVEVIN/RQEVIN
140            CONTINUE
               PMR=SLP(GPLANT(I,J,IP),PMX,PMY,2)
C
C KILL SOME SHRUBS IF SOIL MOISTURE IN ALL SOIL LAYERS
C IS GREATER THAN HMMR % (90%????)
           IF(IP.LE.3.AND.WMIN.GT.HMMR)PMR=1.-GMRED(I,J,IP)
C BIOMASS CHANGE WITH NO GRAZING... PRODUCTION ACCUMULATED
C ONLY UNTIL SEED SET
               DPB=(GPLANT(I,J,IP)-PMR)*RA(I,J,IP)
           IF(IWEEK.LE.IFDATE)TPROD(I,IP)=TPROD(I,IP)+DPB
C BIOMASS CHANGE WITH GRAZING...
               DPB=DPB-CE(I,J,IP)*(1.+CWST)-WE(I,J,IP)
      CE(I,J,IP)=0.0
      WE(I,J,IP)=0.
C
C ADJUST DPB WITH TRANSLOCATION TO OR FROM ROOTS.
C BIOMASS FROM SHOOT TO ROOT AFTER FDATE, FROM
```

```
C ROOT TO SHOOT BEFORE.ADJUST TOTAL PRODN.
C CHEATGRASS HAS NO ROOT STORAGE
C
               IF(IP.GT.6)GO TO 250
               DROOT=0.
               PNGR=DPB/RA(I,J,IP)
               IF(IWEEK-IFDATE)160,160,200
C......................................
C.........BEFORE SEED SET..................
C......................................
160            TPRTS=PRTS*(1.-FLOAT(IWEEK)/FLOAT(IFDATE))
               DROOT=-1.*ROOT(I,J,IP)*TPRTS
C
C IF STANDARD RATE OF TRANSFER (TPRTS) SUFFICIENT
C TO MAINTAIN BIOMASS, DON'T DECREMENT RESERVES FURTHER.
C
               IF(DPB-DROOT.GE.0)GO TO 180
               IF(ROOT(I,J,IP)+DPB.GE.0)DROOT=DPB
               IF(ROOT(I,J,IP)+DPB.LT.0)DROOT=-0.5*ROOT(I,J,IP)
C MAKE CHANGE IN ABOVE GROUND BIOMASS MORE POSITIVE.
C (DROOOT IS NEGATIVE)
C
180            DPB=DPB-DROOT
               TPROD(I,IP)=TPROD(I,IP)-DROOT
               GO TO 230
C......................................
C.........AFTER SEED SET..................
C......................................
200            DROOT=RA(I,J,IP)*PSTR
C
C ACCOUNT FOR ROOT TO SHOOT OR SHOOT TO ROOT TRANSFERS
C
230            ROOT(I,J,IP)=ROOT(I,J,IP)*(1.-PMR)+DROOT
               IF(ROOT(I,J,IP).LT.0)ROOT(I,J,IP)=1.0
               IF(ROOT(I,J,IP).GT.ROOTMX(IP))
     1         ROOT(I,J,IP)=ROOTMX(IP)
C
C CHANGE PLANT BIOMASS.  RESET IF WENT BELOW ZERO OR
C OUTRAGEOUSLY HIGH.
C
250            RA(I,J,IP)=RA(I,J,IP)+DPB
               IF(RA(I,J,IP).LT.0.)RA(I,J,IP)=1.0
                           IF(RA(I,J,IP).GT.PLNTMX(IP))
     1                     RA(I,J,IP)=PLNTMX(IP)
               GO TO 400
C
C PLANT AND ROOT WINTER SURVIVAL.
C
300            RA(I,J,IP)=RA(I,J,IP)*PWS(IP)
               IF(IP.GT.6)GO TO 400
               ROOT(I,J,IP)=ROOT(I,J,IP)*RWS
400            CONTINUE
450         CONTINUE
475   CONTINUE
C
C CALCULATE % COMPOSITION BY WT.
```

```
C
      DO 530 I=1,NFAS
      IF(IOC(I).EQ.0)GO TO 530
      GPTOT=0.
      DO 478 IP=1,7
478   GPCWT(I,IP)=0.
        DO 500 J=1,NRT
         IF(RA(I,J,8).EQ.0)GO TO 500
         PTOT=0.
         DO 480 IP=1,7
         GPCWT(I,IP)=GPCWT(I,IP)+RA(I,J,IP)
480      PTOT=PTOT+RA(I,J,IP)
         GPTOT=GPTOT+PTOT
         DO 490 IP=1,7
      PCWT(I,J,IP)=0
         IF(PTOT.NE.0)PCWT(I,J,IP)=RA(I,J,IP)/PTOT*100.
 490   CONTINUE
500   CONTINUE
      DO 520 IP=1,7
      IF(GPTOT.NE.0.)GPCWT(I,IP)=GPCWT(I,IP)/GPTOT
520   CONTINUE
530   CONTINUE
C
C CALCULATE % COVER
C
      CALL COVER
C
C % PROTEIN CONTENT.
C
      DO 600 IP=1,7
         IF(IP.LE.3)VP(IP)=SLP(IWEEK,SVPX,SVPY,2)
         IF(IP.GE.4.AND.IP.LE.6)VP(IP)=SLP(IWEEK,PVPX,PVPY,2)
         IF(IP.EQ.7)VP(7)=SLP(IWEEK,CVPX,CVPY,2)
600   CONTINUE
      RETURN
      END
      SUBROUTINE COVER
$CONTINUE WITH SAVAL.C RETURN
C
C THIS SUBROUTINE SCALES % COVER OF GRASSES,SHRUBS,
C TREES,CANOPY AND GROUND ACCORDING TO % WT, A
C TRULY FALSE ASSUMPTION.
C
      DO 106 I=1,NFAS
      IF(IOC(I).EQ.0)GO TO 106
      DO 100 J=1,NRT
         IF(RA(I,J,8).EQ.0)GO TO 100
      PC(I,J,1)=0.
C % GRASS COVER
      IF(PWTMAX(J,2).EQ.0)GOTO 20
         PC(I,J,1)=(PCWT(I,J,4)+PCWT(I,J,5)+PCWT(I,J,6)
     1              +PCWT(I,J,7))/PWTMAX(J,2)*PCMAX2(J,3)
C % SHRUB COVER
20    PC(I,J,2)=0.
      IF(PWTMAX(J,1).EQ.0)GO TO 40
         PC(I,J,2)=(PCWT(I,J,1)+PCWT(I,J,2)+PCWT(I,J,3))/
     1              PWTMAX(J,1)*PCMAX2(J,1)
C % TREE COVER
40      PC(I,J,3)=0.
C ************ NEXT STATEMENT TEMPORARILY REMOVED ******
C        IF(J.EQ.9)PC(I,9,3)=PCMAX2(9,1)
C % CANOPY COVER
         PC(I,J,4)=PC(I,J,2)+PC(I,J,3)
C % GROUND COVER (GRASS,LITTER,ROCK AND CANOPY)
C
C RLP=RATIO OF (GRASS+LITTER):GRASS - 40%?
C
         PC(I,J,5)=PC(I,J,1)*RLP+PCMAX2(J,4)+PC(I,J,4)
C
C NORMALIZE "PERCENTAGES".
C
         TOTPCT=PC(I,J,5)+PC(I,J,4)
         IF(TOTPCT.LT.100.)GO TO 100
         PC(I,J,4)=PC(I,J,4)/TOTPCT*100
         PC(I,J,5)=PC(I,J,5)/TOTPCT*100.
100      CONTINUE
106    CONTINUE
         RETURN
         END
      SUBROUTINE LUMP
$CONTINUE WITH SAVAL.C RETURN
C
C THIS SUBROUTINE GROUPS THE TEN SITES IN THE SET FILE TO
C FORM NRT RANGE SITES. ROW K OF NEWRS SPECIFIES THE OLD
C RANGE SITES THAT ARTE GROUPED INTO THE KTH NEW RANGE
C SITE CATEGORY. AT THE SAME TIME THIS SUBROUTINE
C REDUCES MID-SUMMER BIOMASS TO EARLY SPRING. NEW
C RANGE SITE ARRAYS ARE WRITTEN OUT TO UNIT 3 TO
C FORM A NEW SET FILE.
C
C LOOP OVER PASTURES...
C
      DO 100 I=1,NPAS
C
C LOOP OVER NEW RANGE SITES
C
        DO 80 JNEW=1,NRT
        RSANEW=0.
C
C LOOP OVER OLD RANGE SITES THAT MAKE UP NEW RANGE SITE
C
          DO 40 JO=1,10
         JOLD=NEWRS(JNEW,JO)
          IF(JOLD.EQ.0)GO TO 45
          RSAOLD=RA(I,JOLD,8)
          IF(RSAOLD.EQ.0.)GO TO 40
          RSANEW=RSANEW+RSAOLD
C
C LOOP OVER PLANT TYPES CALCULATING WEIGHTED SUMS OF PLANT
C BIOMASS. RANEW IS INITIALIZED TO ZERO IN SET FILE.
C
           DO 10 IP=1,7
           RANEW(I,JNEW,IP)=RANEW(I,JNEW,IP)+
     1                           RA(I,JOLD,IP)*RSAOLD
10         CONTINUE
C
C LOOP OVER SOIL MOISTURE LAYERS CALCULATING WIGHTED SUMS
C OF AVAILABLE WATER CAPACITY.
           DO 20 IS=1,3
           AWCNEW(I,JNEW,IS)=AWCNEW(I,JNEW,IS)+
     1                            AWC(JOLD,IS)*RSAOLD
20         CONTINUE
40       CONTINUE
C
C CONVERT WEIGHTED BIOMASS SUM TO WEIGHTED AVERAGE SPRING BIOMASS.
C CONVERT WEIGHTED AWC SUM TO WEIGHTED AVERAGE AWC.
45        DO 50 IP=1,7
       IF(RSANEW.EQ.0)GO TO 50
          RANEW(I,JNEW,IP)=SPB*(RANEW(I,JNEW,IP)/RSANEW)**
     1                         SPBEXP
50        CONTINUE
          DO 55 IS=1,3
       IF(RSANEW.EQ.0)GO TO 55
          AWCNEW(I,JNEW,IS)=AWCNEW(I,JNEW,IS)/RSANEW
55        CONTINUE
C
C WRITE OUT NEW VALUES IN SET FILE FORM.
C
         WRITE(3,60)I,JNEW,(RANEW(I,JNEW,IP),IP=1,7),RSANEW
60       FORMAT('S RA(',I2,',',I1,',ALL)=',8F6.0)
         WRITE(3,70)I,JNEW,(AWCNEW(I,JNEW,IS),IS=1,3)
70       FORMAT('S AWCNEW(',I2,',',I1,',ALL)=',3F5.2)
80       CONTINUE
100    CONTINUE
       RETURN
       END
```

HYDROLOGY SUBMODEL

This submodel is described in Section 4 of the report.

```
      SUBROUTINE WAT(ITIME)
$CONTINUE WITH SAVAL.C RETURN
C
C SETUP INITIAL CONDITIONS IN FIRST RUN
      IF(ITIME.NE.1) GOTO 10
      DO 6  I=1, NPAS
      DO 5  J=1, NRT
      DO 4  K=1, 3
      SOWAT(I,J,K) = 0.9*AWCNEW(I,J,K)*WATRES(K)
    4 CONTINUE
      IF ((I.NE.8).AND.(I.NE.9)) GOTO 5
      SNOPAC(I,J)=1.
      FREZDP(I,J)=6.
    5 CONTINUE
    6 CONTINUE
   10 CONTINUE
      NSTEP = NSTEP + 1
      NDAYS = 7
      IWFLG = 0
      IF (NSTEP.NE.2) GOTO 30
C ZERO ACUMULATORS AT START OF YEAR
      TSEDG = 0.0
      TSEDM = 0.0
      DO 20  I=1, 3
      FTOT(I) = 0.
   20 CONTINUE
C
C ZERO WEEKLY ACCUMULATORS
   30 DO 60  I=1, NPAS
      TMAX(I) = 0.
   60 CONTINUE
      DO 65  I=1, 3
      FWTOT(I) = 0.
   65 CONTINUE
      WQUAL = 0.
      DO 80  I=1, NPAS
      DO 75  J=1, NRT
      PEVAP(I,J)=0.
      DO 70  K=1, 3
      SO(I,J,K) = 0.
   70 CONTINUE
   75 CONTINUE
   80 CONTINUE
      DO 90  I=1, NPAS
      PRECIP(I) = 0.
   90 CONTINUE
      IF (NSTEP.LE.NWEEKS) GOTO 100
C
C SET UP WINTER STEP
      NDAYS = WINDAY
      IWFLG = 1
      NSTEP = 0
C
C       START MAIN LOOP OVER DAYS IN THE CURRENT TIME STEP
C       --------------------------------------------------
C
  100 DO 5000  IDAY=1, NDAYS
      JDAY = JDAY + 1
      IF (JDAY.GE.366) JDAY = 1
C
C INITIALIZE RAIN PER PASTURE
      DO 110  I=1, NPAS
      DPREC(I) = PREC(JDAY)
  110 CONTINUE
      DPREC(8) = PREC(JDAY) * PMULT
      DPREC(9) = PREC(JDAY) * PMULT
C
C
C       START MAIN LOOPS OVER PASTURES AND RANGE TYPES
C
```

```
C
      DO 1000 IPAS=1, NPAS
      DO 900  IRTYPE=1, NRT
      IF (RA(IPAS,IRTYPE,8).EQ.0) GOTO 900
      IF((IOC(IPAS).EQ.0).AND.(IPAS.NE.9)) GOTO 900
C
C                EVAPOTRANSPIRATION
C
C POTENTIAL EVAPOTRANSPIRATION
      RADLAN = 200. + 600.*SIN((JDAY/365.)*3.14159)
      IF (LUPTR(IPAS).EQ.1) DMTEMP =
     1  ((TMAXL(JDAY)*TMULT) +
     2   (TMINL(JDAY)*TMULT)) / 2.
      IF (LUPTR(IPAS).EQ.0) DMTEMP = (TMAXL(JDAY)+TMINL(JDAY))/2.
      ETPOT = ((0.014*DMTEMP - 0.37)*RADLAN) / 580
      IF (ETPOT.LT.0.) ETPOT = 0.
C
C PERCENT ACTIVE CANOPY
      PACAN = SIN((((FLOAT(JDAY))-66.)/365.)*3.14159)
      IF ((JDAY.LT.66).OR.(JDAY.GT.(NWEEKS*7+66))) PACAN = 0.
C
C ACTUAL ET BY PLANTS
      IF ((ITIME.NE.1).AND.(IOC(IPAS).EQ.1)) PCDUM=PC(IPAS,IRTYPE,5
)
      IF ((ITIME.EQ.1).OR.(IOC(IPAS).EQ.0)) PCDUM=PCMAX(IRTYPE,5)
      ETPLNT = PCDUM * TCOF * ETPOT * PACAN / 100.
      ETSUM = 0.
      DO 210  I=1, 3
      ETSUM = ETSUM + (PACAN*SOWAT(IPAS,IRTYPE,I)) /
     1         (AWCNEW(IPAS,IRTYPE,I)*WATRES(I))
  210 CONTINUE
      ETPLNT = ETPLNT * ETSUM / 3.
C
C ET FROM BARE SOIL
      ETSOIL = (100.-PCDUM)*(SOWAT(IPAS,IRTYPE,1)/WATRES(1))
     1          * ETPOT / (AWCNEW(IPAS,IRTYPE,1) * 100.)
C
C REMOVE ET FROM SOIL LAYERS
      SOWAT(IPAS,IRTYPE,1)=SOWAT(IPAS,IRTYPE,1) - ETSOIL
      IF (SOWAT(IPAS,IRTYPE,1).LT.0.) SOWAT(IPAS,IRTYPE,1)=0.
      ETPREM = ETPLNT
      DO  400  ILEAK=1, 3
      IF (ETPLNT.LT.SOWAT(IPAS,IRTYPE,ILEAK)) GOTO 300
      ETPLNT=ETPLNT - SOWAT(IPAS,IRTYPE,ILEAK)
      SOWAT(IPAS,IRTYPE,ILEAK)=0.
      GOTO 400
  300 CONTINUE
      SOWAT(IPAS,IRTYPE,ILEAK)=SOWAT(IPAS,IRTYPE,ILEAK)-ETPLNT
      PEVAP(IPAS,IRTYPE) = ETPREM + PEVAP(IPAS,IRTYPE)
      GOTO 500
  400 CONTINUE
      PEVAP(IPAS,IRTYPE) = ETPREM - ETPLNT
     1   + PEVAP(IPAS,IRTYPE)
  500 CONTINUE
C
C                       SNOW PACK MANIPULATION
```

```
C
      IF (DMTEMP.GT.32) GOTO 600
C
C ACCUMULATION
      SNOPAC(IPAS,IRTYPE)=SNOPAC(IPAS,IRTYPE)+DPREC(IPAS)
      DPRECT(IPAS) = 0.
      GOTO 700
C
C MELTING
  600 CONTINUE
      SMELT = (DMTEMP - 32) / 10.
      IF (SMELT.LT.SNOPAC(IPAS,IRTYPE)) GOTO 610
      DPRECT(IPAS)=DPREC(IPAS) + SNOPAC(IPAS,IRTYPE)
      SNOPAC(IPAS,IRTYPE) = 0.
      GOTO 620
  610 CONTINUE
      SNOPAC(IPAS,IRTYPE)=SNOPAC(IPAS,IRTYPE) - SMELT
      DPRECT(IPAS) = DPREC(IPAS) + SMELT
  620 CONTINUE
  700 CONTINUE
C
C                 RUNOFF / INFILTRATION
C
C RUNOFF
      APAR=CNA(IPTR(IRTYPE))
      BPAR=CNB(IPTR(IRTYPE))
      CN = APAR - BPAR*PCDUM
      SMAX = (1000./CN) - 10.
      WSOW = 0
      AWSOW = 0
      DO 720  I=1, 3
      WSOW=WSOW+SOWAT(IPAS,IRTYPE,I)/WATRES(I)
      AWSOW=AWSOW+AWCNEW(IPAS,IRTYPE,I)
  720 CONTINUE
      WSOW = WSOW / 3.
      AWSOW = AWSOW / 3.
      S=SMAX*(AWSOW - WSOW) / AWSOW
      RUNOFF(IPAS,IRTYPE)=((DPRECT(IPAS)-0.2*S)**2) /
     1    (DPRECT(IPAS) + 0.8*S)
      RUNOFF(IPAS,IRTYPE) = RUNOFF(IPAS,IRTYPE) * RFUDG
      IF (DPRECT(IPAS).LT.(0.2*S)) RUNOFF(IPAS,IRTYPE)=0.
C
C INFILTRATION
      WATIN = DPRECT(IPAS) - RUNOFF(IPAS,IRTYPE)
      IF (WATIN.LT.0.) WATIN=0.
      DO 800  IFIL=1, 3
      IF ((WATIN+SOWAT(IPAS,IRTYPE,IFIL)).LT.(WATRES(IFIL)
     1      *AWCNEW(IPAS,IRTYPE,IFIL)))  GOTO 750
      WATIN=WATIN-((WATRES(IFIL)*AWCNEW(IPAS,IRTYPE,IFIL)) -
     1       SOWAT(IPAS,IRTYPE,IFIL))
      SOWAT(IPAS,IRTYPE,IFIL)=WATRES(IFIL)*AWCNEW(IPAS,IRTYPE,IFIL)
      GOTO 800
  750 CONTINUE
      SOWAT(IPAS,IRTYPE,IFIL)=SOWAT(IPAS,IRTYPE,IFIL) + WATIN
      GOTO 850
  800 CONTINUE
  850 CONTINUE
C
C                DEPTH OF FROZEN SOIL
C
      FREZDP(IPAS,IRTYPE)=FREZDP(IPAS,IRTYPE) +
     1     0.1 * (32-DMTEMP)
      IF (FREZDP(IPAS,IRTYPE).LT.0.) FREZDP(IPAS,IRTYPE)=0.
      IF (FREZDP(IPAS,IRTYPE).GT.30.) FREZDP(IPAS,IRTYPE)=30.
C
C                  EROSION
C
      RFAC = 10. * (DPRECT(IPAS)**0.0374)
      CFAC = 10**(-0.552-(0.016*PCDUM))
      SOILOF(IPAS,IRTYPE)=ER(IRTYPE)*RFAC*XLS(IRTYPE)*
     1      CFAC*PMECH
  900 CONTINUE
C
C END OF SOIL TYPE LOOP
C
 1000 CONTINUE
C
C END OF PASTURE LOOP
C
C
C          FLOWS IN GANCE MAHALA AND NORTH FORK
C
      FLGNC = 0.
      FLMAH = 0.
      DO 1100  I=1, NRT
      FLGNC = FLGNC + RUNOFF(9,I)*ARGNC(I)
      FLMAH = FLMAH + RUNOFF(9,I)*ARMAH(I)
 1100 CONTINUE
      FLMAH = FLMAH * FLFUDG * CUFS
      OS = (1000./OCN) - 10.
      ORUN = ((DPRECT(9)-0.2*OS)**2) / (DPRECT(9) + 0.8*OS)
      IF (DPRECT(9).LT.(0.2*OS)) ORUN = 0.
      FLGNC=(FLGNC + ORUN*OAR) * FLFUDG * CUFS
      FTOT(1) = FTOT(1) + FLGNC*AFCON
      FTOT(2) = FTOT(2) + FLMAH*AFCON
      FTOT(3) = FTOT(3) + NFFLOW(NSTEP+1) * AFCON
      FWTOT(1)=FWTOT(1)+FLGNC*AFCON
      FWTOT(2)=FWTOT(2)+FLMAH*AFCON
      FWTOT(3)=FWTOT(3)+NFFLOW(NSTEP+1)*AFCON
C
C           WATER QUALITY
C
C UPLAND EROSION REACHING STREAMS
      UEGNC = 0.
      UEMAH = 0.
      DO 1200  I=1, NRT
      UEGNC = UEGNC + SOILOF(9,I)*ARGNC(I)
      UEMAH = UEMAH + SOILOF(9,I)*ARMAH(I)
 1200 CONTINUE
      UEGNC = UEGNC*SEDDEL
      UEMAH = UEMAH*SEDDEL
      TSEDG = TSEDG + UEGNC
      TSEDM = TSEDM + UEMAH
C
C BANK EROSION INTO STREAMS
      BETOT = CATFAC * CU(9) * RM(9)
C
C WATER QUALITY
      WATQAL=(BETOT+UEGNC+UEMAH) /
     1        (FLMAH + FLGNC + 0.001)
C
C              BANK STABILITY
C
      WTWOOD = 0.
      DO 1400  I=1, 3
      IF ((ITIME.NE.1)) PCDUM1=PC(9,1,I)
      IF ((ITIME.NE.1)) PCDUM2=PC(9,2,I)
      IF ((ITIME.EQ.1)) PCDUM1=PCMAX(1,I)
      IF ((ITIME.EQ.1)) PCDUM2=PCMAX(2,I)
      J=1+I
      WTWOOD=WTWOOD + J*((PCDUM1+PCDUM2)/2.)
 1400 CONTINUE
      WTWOOD = WTWOOD / 4
      BSTAB = BSTB1*WTWOOD - BSTB2*CU(9)
      IF (BSTAB.GT.100.) BSTAB = 100.
C
C             MAKE UP WEEKLY/BY TIME STEP TOTALS
C
C TEMPERATURE
      DO 1500  I=1, NPAS
      IF ((I.EQ.8).OR.(I.EQ.9)) GOTO 1500
      TMAX(I) = TMAX(I) + TMAXL(JDAY)
 1500 CONTINUE
      TMAX(8) = TMAX(8) + TMAXL(JDAY) * TMULT
      TMAX(9) = TMAX(9) + TMAXL(JDAY) * TMULT
C
C SOIL MOISTURE
      DO 1700  I=1, NPAS
      DO 1650  J=1, NRT
      DO 1600  K=1, 3
      SO(I,J,K) = SOFDG*100.*(SOWAT(I,J,K)/((AWCNEW(I,J,K)+0.0001)
     1              *WATRES(K))) + SO(I,J,K)
 1600 CONTINUE
 1650 CONTINUE
 1700 CONTINUE
C
C WATER QUALITY
      WQUAL = WQUAL + WATQAL
C
C           END OF DAY LOOP
C           ---------------
C
 5000 CONTINUE
C
C       CALCULATE AVERAGE VALUES
C TEMPERATURE
      DO 6000  I=1, NPAS
      TMAX(I) = TMAX(I) / NDAYS
 6000 CONTINUE
C
C SOIL MOISTURE
      DO 7000  I=1, NFAS
      DO 6900  J=1, NRT
      DO 6800  K=1, 3
      SO(I,J,K) = SO(I,J,K) / NDAYS
 6800 CONTINUE
 6900 CONTINUE
 7000 CONTINUE
C
C WATER QUALITY
      WQUAL = WQUAL / NDAYS
C
C
      RETURN
      END
```

CATTLE AND ECONOMICS SUBMODEL

This submodel is described in Section 5 of the report.

```
      SUBROUTINE VIANDE
$CONTINUE WITH SAVAL.C RETURN
C
      IF(IWEEK.LT.ISTR)RETURN
      IF(IWEEK.GT.ISTR.AND.IWEEK.LT.IENR)GO TO 100
      IF(IWEEK.EQ.IENR) GO TO 1000
      IF(IWEEK.GT.IENR)RETURN
C
C.....SHIFT PASTURES
C
      DO 30 I=1,9
      IF(IPCNT(I).EQ.IPYN(I)) GO TO 35
      IPCNT(I)=IPCNT(I)+1
      GO TO 30
 35   CONTINUE
      IGR(I)=IPTO(IGR(I))
      IPCNT(I)=1
 30   CONTINUE
      IUSE=0
      NPAST=0
      TGWA=0.
      TGWAO=TGWA
      IGRT=0
C
C.....SPRING CALVING, ETC.
C
      COW(1)=COW(1)+COWB+COW(2)
      COWW(1)=(COWW(1)*COW(1)+COWW(2)*COW(2))/(COW(1)+COW(2))
      COW(3)=YRB
      COWW(3)=YEARW
      COW(2)=CALF+CLFB
      COWW(2)=CALFW
      TCOW=COW(1)+COW(2)+COW(3)
  100 CONTINUE
C
C.....SELECT THE PASTURE, IF NECESSARY
C
      IF(IGRT.LT.1) GO TO 105
      IF(NPAST.EQ.7) GO TO 603
      IF(NPAST.EQ.9) RETURN
      GO TO 107
  105 CONTINUE
      NPAST=NPAST+1
      IF(NPAST.EQ.7) GO TO 603
      IF(NPAST.EQ.9) RETURN
      DO 103 I=1,NPMAX
      IF(IGR(I).NE.NPAST) GO TO 103
      IUSE=I
      GO TO 104
  103 CONTINUE
  104 CONTINUE
  107 CONTINUE
      IF(IOC(IUSE).NE.1) GO TO 603
      IF(IMUNCH.GT.1) CALL EATUM
      IF(IMUNCH.GT.1) GO TO 1999
C
C.....CALCULATE TOTAL HERD REQUIREMENTS~ FOR THE WEEK
C
      TTREQ=0.
      DO 40 I=1,3
      TREQ(I)=((YII+SLI*COWW(I)*.454)/.454)*DPW*COW(I)
      TTREQ=TTREQ+TREQ(I)
   40 CONTINUE
      DO 150 K=1,3
      TDN(K)=0.
      BEAT(K)=0.
  150 CONTINUE
C
C.....CATTLE DAYS ON RIPARIAN HABITAT
C
      DO 151 K=1,NPAS
      CU(K)=0.0
  151 CONTINUE
      CU(IUSE)=
     >(COW(1)+COW(2)+COW(3))*DPW/(RA(IUSE,3,8)+.0001)
C
C.....START MUNCHING ON FORAGE, FIRST OVER RANGE TYPES
C
      DO 500 IRR=1,NRT
      IR=NRT-IRR+1
      IF(RA(IUSE,IR,8).LE.1.0E-5) GO TO 500
C
C.....LOOP OVER SPECIES
C
      DO 110 K=1,7
      CE(IUSE,IR,K)=0.
```

```
 110    CONTINUE
        DO 400 IP=1,7
        IPP=IPREF(IP)
C
C.....LOOP OVER WATER NEARNESS TYPES
C
        DO 300 IW=9,IWM
        IF(IW.EQ.9.AND.IGRT.EQ.0)TGWA=TGWA+RA(IUSE,IR,8)*RA(IUSE,IR,I
W)
        IF(IW.EQ.9)
       >X=RA(IUSE,IR,8)*RA(IUSE,IR,IPP)*RA(IUSE,IR,IW)
        IF(IW.EQ.10)
       >       X=RA(IUSE,IR,IPP)*RA(IUSE,IR,8)*(1.-RA(IUSE,IR,IW-1))
        XTEST=-1*TTREQ/(X+0.00001)
        IF (XTEST.GT.174.) XTEST=174.
        IF (XTEST.LT.-180.) XTEST=-180.
        XX=X*(1.0-EXP(XTEST))
        CE(IUSE,IR,IPP)=
       >CE(IUSE,IR,IPP)+XX
C
C.....CALCULATE INGESTION OF NUTRIENTS BY CATTLE
C
        DO 200 K=1,3
        XXX=XX*TREQ(K)/(TTREQ*DPW*COW(K)+.00001)
        TREQ(K)=AMAX1(TREQ(K)-XXX,0.0)
C       WRITE(6,610) X,XX,XXX
C610    FORMAT(1X,3F15.6)
        TDN(K)=TDN(K)+(SLTDN(IPP)*(VP(IPP)/100.)+YTDN(IPP))*XXX
        BEAT(K)=BEAT(K)+XXX
 200    CONTINUE
        TTREQ=TTREQ-BEAT(1)-BEAT(2)-BEAT(3)
        IF(TTREQ.LT.1.0E-5)GO TO 401
 300    CONTINUE
 400    CONTINUE
 401    CONTINUE
        DO 450 K=1,7
        CE(IUSE,IR,K)=CE(IUSE,IR,K)/(RA(IUSE,IR,8)+.0001)
 450    CONTINUE
        IF(TTREQ.LT.1.0E-5)GO TO 501
 500    CONTINUE
 501    CONTINUE
C
C.....CALCULATE GROWTH
C
   1999 CONTINUE
        IF(IGROW.GT.0) CALL OBESE
        IF(IGROW.GT.0) GO TO 603
        DO 560 K=1,3
        DO 550 I=1,7
        IF(COWW(K).GE.WGAR(I,1)*2.2.AND.COWW(K).LT.WGAR(I+1,1)*2.2)
       >        GO TO 555
 550    CONTINUE
 555    CONTINUE
        DO 558 J=2,6
        XWG(J-1)=
       >        (WGAR(I+1,J)-WGAR(I,J))/(WGAR(I+1,1)-WGAR(I,1))*
```

```
     >      ((COWW(K)/2.2)-WGAR(I,1))+WGAR(I,J)
  558 CONTINUE
      WGAIN(K)=SLP(TDN(K)/2.2,XWG,YWG,5)*2.2*DPW
      COWW(K)=COWW(K)+WGAIN(K)
  560 CONTINUE
C
C.....DECISION RULES FOR MOVING TO NEW PASTURES
C
  603 CONTINUE
      IGRT=IGRT+1
      IF(IGRT.GE.IPW(NPAST))IGRT=0
      RETURN
C
C.....THIS IS THE FALL PERIOD
C
 1000 CONTINUE
      CALFS=COWW(2)*PCS*COW(2)
      COW(2)=COW(2)*(1.-PCS)
      COWS=
     >COWW(1)*AMAX1(0.0,(COW(1)+COW(2))-COWMAX)
      COW(1)=COW(1)-COWS/(COWW(1)+.00001)
      YEARS=COW(3)*COWW(3)
      COW(3)=0.
      PBSLD=CALFS+COWS+YEARS
      BEEF=PPCOW*COWS+PPCLF*CALFS+PPYR*YEARS
C
C.....CALCULATE CALVING RATE
C
      CALF=
     >      SLP(COWW(1),XCLF,YCLF,6)*COW(1)
      PCALF=(CALF/(COW(1)+.00001))*100.
      IF(ISTOP.GT.0) RETURN
C
C.....HAY STUFF
C
      THAYG=0.0
      DO 1010 I=1,3
      THAYG=THAYG+HAYP(I)*2000.
 1010 CONTINUE
      THAYR=0.0
      DO 1020 I=1,2
      HAYR(I)=DPWN*((YII+SLI*COWW(I)*.454)/.454)*COW(I)
      HAYR(I)=HAYR(I)+HPP(I)*AMAX1(0.0,CMIN(I)-COWW(I))*COW(I)
      THAYR=THAYR+HAYR(I)
 1020 CONTINUE
      HAYB=AMIN1(THAYR-THAYG,BUYHAY*2000.)*IAHB
      HAYS=AMAX1(THAYG-THAYR,0.0)*IAHS
      THAY=THAYG+HAYB
      HAYB=HAYB/2000.
      IF(HAYB.LT.0.)HAYB=0.
      HAYS=HAYS/2000.
C
C.....GROW COWS OVER WINTER
C
      DO 1030 I=1,2
      COWW(I)=COWW(I)+
          >SLP(HAYR(I)*THAY/(1.0E-5+(DPWN*COW(I)*THAYR)),XWNG,YWNG,3)*DP
     WN
 1030 CONTINUE
      IF(IECON.LT.1)RETURN
      COSTS=
     >     THAYG*DGH+HAYB*DBH+FC+VC*TCOW+
     >     DAW*(TGWA-TGWAO)
      REV=BEEF+DSH*HAYS
      RNP=COSTS-(FC/2.)
      GVO=XM1*RNP
      CVA=XM2*GVO
      RNA=XM3*RNP
      RETURN
      END

      SUBROUTINE EATUM
$CONTINUE WITH SAVAL.C RETURN
C
      TTREQ=0.
      DO 40 I=1,3
      TREQ(I)=((YII+SLI*COWW(I)*.454)/.454)*DPW*COW(I)
      H(I)=1.0/((TREQ(I)+.0000001)/(COW(I)+.0000001))
      TTREQ=TTREQ+TREQ(I)
   40 CONTINUE
C
C.....BOTTOM OF RESPONSE
C
      DO 100 I=1,3
      TDN(I)=0.
      FBOT=1.
      DO 90 IF=1,7
      DO 90 IR=1,3
      DO 90 IW=1,2
      FBOT=FBOT+ALPH(I)*H(I)*PREFF(IF,IR,IW)*RA(IUSE,IR,IF)
      TDIE(IR,IR,IW)=0.
      TTAT(I,IF,IR,IW)=0.
   90 CONTINUE
      DO 95 IF=1,7
      DO 95 IR=1,3
      DO 95 IW=1,2
      X=ALPH(I)*PREFF(IF,IR,IW)*(COW(I)/(RA(IUSE,IR,8)+.000001))/FB
OT
      IF(X.GT.100.)X=100.
      TDIE(IF,IR,IW)=TDIE(IF,IR,IW)+X
      TTAT(I,IF,IR,IW)=X
   95 CONTINUE
  100 CONTINUE
C
C.....CALCULATE CONSUMPTION, LOSS
C
      DO 200 IF=1,7
      XX=SLTDN(IF)*(VP(IF)/100.)+YTDN(IF)
      DO 200 IR=1,3
      DO 200 IW=1,2
      X=1.0-EXP(-TDIE(IF,IR,IW))
      DO 150 I=1,3
     Y=(TTAT(I,IF,IR,IW)/TDIE(IF,IR,IW)+.000001)*X*RA(IUSE,IR,8)*X
X
    )*RA(IUSE,IR,8+IW)*RA(IUSE,IR,IF)/(COW(I)+.000001)
     TDN(I)=TDN(I)+Y/(DPW+.0000001)
 150 CONTINUE
     CE(IUSE,IR,IF)=CE(IUSE,IR,IF)*(1.-((X*RA(IUSE,IR,8)*RA(IUSE,I
R,8+IW))/RA(IUSE,IR,8)+.00001))
     CE(IUSE,IR,IF)=CE(IUSE,IR,IF)*(1.-((X*RA(IUSE,IR,8)*RA(IUSE,I
R,8+IW))/RA(IUSE,IR,8)+.00001))
 200 CONTINUE
     DO 999 IR=1,NRT
     DO 999 IF=1,7
     CE(IUSE,IR,IF)=RA(IUSE,IR,IF)*(1.-CE(IUSE,IR,IF))
     RETURN
     END

     SUBROUTINE OBESE
$CONTINUE WITH SAVAL.C RETURN
     DO 50 I=1,3
     WGAIN(I)=0.
 50  CONTINUE
     DO 100 I=1,3
     DO 85 IR=1,NRT
     DO 80 IF=1,7
     TT=(SLTDN(IF))*(VP(IF)/100.)+YTDN(IF)*100.
     EM=TT*EMP
     F=EXP(FP1-FP2*EM)
     EMN=EMNP/F
     GEN=GENP1-GENP2*F
     REMN=PM1*COWW(I)**PM2
     RIN=REMN/EMN
     SURP=(CE(IUSE,IR,IF)*RA(IUSE,IR,8)/(COW(I)*DPW+.0001))-RIN
     DNEG=SURP*GEN
     GO TO (1,1,2),I
 1   CONTINUE
     X=G1(1)*SQRT(G2(1)+G3(1)*(DNEG/COWW(I)**PM2))-G4(1)
     GO TO 10
 2   CONTINUE
     X=G1(2)*SQRT(G2(2)+G3(2)*(DNEG/(COWW(I)**PM2)))-G4(2)
 10  CONTINUE
     WGAIN(I)=WGAIN(I)+X
 80  CONTINUE
 85  CONTINUE
 100 CONTINUE
     DO 200 I=1,3
     COWW(I)=COWW(I)+WGAIN(I)*DPW
 200 CONTINUE
     RETURN
     END
```

WILDLIFE SUBMODEL

This submodel is described in Section 6 of the report.

```
       SUBROUTINE WILD
#CONTINUE WITH SAVAL.C RETURN
C
C  SECOND VERSION OF SAVAL WILDLIFE MODEL CREATED AFTER WORKSHOP
C  JAN 3,1982
C
      M=IMONTH
      IF(IWEEK.NE.1)GO TO 3
      DO 2 I=1,3
      IC(I)=0
 2    CONTINUE
 3    CONTINUE
 1    IF(IWEEK.NE.1)GOTO 10
C
C  * * * * * * * *   D E E R   M O D E L  * * * * * * * * * *
C
C  OVER WINTER MORTALITY
C
      HEALA=DENERA/(ANEED*38)
      HEALF=DENERF/(FNEED*38.)
      DMALE=DMALE*SLP(HEALA,XMALED,YMALED,2)
       DFEM=DFEM*SLP(HEALA,XFEM,YFEM,2)
      FAWN=FAWN*SLP(HEALF,XFNY,YFNY,2)
C
C  ADD FAWNS INTO ADULT POPULATION
C
      DMALE=DMALE+FAWN*FPERC
      DFEM=DFEM+FAWN*(1.-FPERC)
      TDEER=DMALE+DFEM
      FAWN=0
      DENERA=0
      DENERF=0
      DSEAS=0
      DO 5 I=1,3
      ITRIG(I)=0
      IC(I)=0
 5    CONTINUE
  10   CONTINUE
C
C  SEE IF FORBS ARE GROWING IN RESPECTIVE PASTURES
C  LOWER SHEEP
      DO 20 J=1,3
      IF(GPLANT(6,J,4).GT.0)ITRIG(1)=1
 20   CONTINUE
      IF(ITRIG(1).GT.0)IC(1)=IC(1)+1
C
C  IF MORE THAN 8 WEEKS HAVE PASSED AND NO GROWTH EVIDENT THEN MOVE
C  DEER ONTO LOWLANS
C
      IF(IWEEK.GT.8.AND.ITRIG(1).EQ.0)IC(1)=2
      IF(IC(1).LT.2)GOTO 105
      IF(DSEAS.GE.2)GOTO 50
C
C  DEER ARE MOVING INTO LOWER PASTURE
      DSEAS=1
      DEER=FRAC*(DFEM+DMALE)
      FAWN=0
      IF(IC(1).EQ.2)GOTO 100
  50  CONTINUE
C
C  SEE IF FORBS ARE GROWING IN UPPER SHEEP
      DO 60 J=1,3
      IF(GPLANT(7,J,4).GT.0..OR.GPLANT(5,J,4).GT.0.)ITRIG(2)=1
  60  CONTINUE
      IF(ITRIG(2).GT.0)IC(2)=IC(2)+1
      IF(IC(2).LT.2)GOTO 100
      IF(DSEAS.GE.3)GOTO 80
C
C  DEER ARE MOVING INTO MIDDLE ELEV. PASTURES
      DSEAS=2
      DEER=DFEM+DMALE
  65  CONTINUE
      IF(IC(2).EQ.2)GOTO 100
C
C  SEE IF FORBS ARE GROWING IN INDEPENDANCE PASTURES
  80  CONTINUE
      DO 85 J=1,3
      IF(GPLANT(7,J,4).GT.0.)ITRIG(3)=1
  85  CONTINUE
      IF(ITRIG(3).GT.0)IC(3)=IC(3)+1
      IF(IC(3).LT.2)GOTO 100
      DSEAS=3
      DEER=DFEM+DMALE
 100  CONTINUE
C
C  ALLOW DEER TO EAT FORAGE
      GOTO 499
 105  CONTINUE
C
C  FAWNS ARE BORN IN WEEK 10 (JUNE 1)
      IF(IWEEK.EQ.10)FAWN=SLP(HEALA,XFAW,YFAW,2)*DFEM
C
C  HUNT MALE DEER
      HDAYS=HFRAC*PERMIT*DAYH/37
      XKILL=SLP(DMALE,HHX,HHY,3)
      TKILL=HDAYS*XKILL
      DMALE=DMALE-TKILL
      IF(DMALE.LT.1.)DMALE=1.
      GO TO 525
C
C   D E E R   I N G E S T I O N   M O D E L
C
 499  CONTINUE
      IFLAG=DSEAS
      TOTIN=0.
      TOTVEG=0.
C  AMOUNT DEER WANT TO EAT
      TDEMDA=DEER*DINGW(2)
      TDEMDF=FAWN*DINGW(1)
      TOTIN=TDEMDA+TDEMDF
      IX=NPERP(IFLAG)
```

```
C  LOOP OVER PASTURES
      DO 500 I=1,IX
      II=NPASD(IFLAG,I)
      JX=NPERT(IFLAG)
C  LOOP OVER RANGE TYPES
      DO 500 J=1,JX
      JJ=NTYPE(IFLAG,J)
C  LOOP OVER 7 PLANT GROUPS
      DO 500 K=1,7
C
C  SUBTRACT VEG EATEN BY CATTLE THIS WEEK IF ANY
      RRA(II,JJ,K)=RA(II,JJ,K)-CE(II,JJ,K)
      IF(RRA(II,JJ,K).LT.0.)RRA(II,JJ,K)=0.
C  OVREALL WEIGHTED FOOD AMOUNT AND PERCENT OF DIET
      AMT=RRA(II,JJ,K)*RA(II,JJ,8)
C  TOTAL BIOMASS WEIGHTED BY PREF IN AREA USED DURING CURRENT SEASO
N
C
      TOTVEG=TOTVEG+PREF(K,M)*AMT
 500  CONTINUE
      DO 505 I=1,IX
      II=NPASD(IFLAG,I)
      DO 505 J=1,JX
      JJ=NTYPE(IFLAG,J)
      DO 505 K=1,7
C
C  DETERMINE PROP'N OF EACH VEG TYPE
      AMT=RRA(II,JJ,K)*RA(II,JJ,8)
      PERIN(II,JJ,K)=0.
      IF(TOTVEG.GT.0.)PERIN(II,JJ,K)=PREF(K,M)*AMT/TOTVEG
C
C  AMOUNT OF VEGETATION EATEN
      WE(II,JJ,K)=0
C
C  TOTAL BIOMASS OF EACH VEG. TYPE EATEN BY DEER
      IF(RA(II,JJ,8).GT.0)WE(II,JJ,K)=PERIN(II,JJ,K)*TOTIN/RA(II,JJ
,8)
C
C  CHECK THAT DEER NOT EATING MORE THAN AVAILABLE
      IF(WE(II,JJ,K).GT.RRA(II,JJ,K))WE(II,JJ,K)=RRA(II,JJ,K)
 510  CONTINUE
C
C  ADD WHAT DEER GET INTO ENERGY POOL( PER INDIVIDUAL)
      IF(TOTIN.LE.0..OR.DEER.LE.0.)GOTO 505
      DENERA=DENERA+WE(II,JJ,K)*RA(II,JJ,8)*(TDEMDA/TOTIN)*CAL(K,M)
/DEER
      IF(TOTIN.LE.0..OR.FAWN.LE.0.)GOTO 505
      DENERF=DENERF+WE(II,JJ,K)*RA(II,JJ,8)*(TDEMDF/TOTIN)*CAL(K,M)
/FAWN
 505  CONTINUE
      GOTO 105
C
C * * *  S A G E   G R O U S E  M O D E L  * * * * * * *
C
C  CALCULATE VARIOUS AVERAGES
C  AVERAGE FORBS AND GRASSES  APRIL 1  JUNE 15
```

```
 525  IF(IWEEK.GT.1)GOTO 550
      DO 540 I=1,5
      FA1J15(I)=0
      GA1J15(I)=0
      FJ1S1(I)=0
      GJ1S1(I)=0
      CM1M31(I)=0
      FM15S3(I)=0
      CM15S3(I)=0
      GM15S3(I)=0
 540   CONTINUE
 550  CONTINUE
      IF(IWEEK.GT.11)GOTO 630
      IF(IWEEK.LT.3)GOTO 630
C  LOOP OVER STRUTTING GROUNDS
      DO 620 I=1,ISAGE
C  SET UP FOR CORRESSPONDING PASTURES
      II=ISTRUT(I)
      GA=0
C  CALCULATE AVERAGE FORBS OVER 2 RANGE SITES - LOAMY AND CLAY
      FA=(RA(II,1,4)+RA(II,2,4))/2.
C  CALCULATE AVERAGE DENSITY OF GRASSES OVER 2 RANGE SITES AND
C  3 PLANT GROUPS
      DO 619 K=5,7
      GA=GA+(RA(II,1,K)+RA(II,2,K))/6.
 619  CONTINUE
C  NOW AVERAGE OVER TIME  - 9 WEEKS
      FA1J15(I)=FA1J15(I)+FA/9.
      GA1J15(I)=GA1J15(I)+GA/9.
 620  CONTINUE
 630  CONTINUE
C
C  AVERAGE FORBS AND GRASSES  JUNE1  SEPT1
      IF(IWEEK.LT.12)GOTO 640
      IF(IWEEK.GT.24)GOTO 640
      DO 635 I=1,ISAGE
      II=ISTRUT(I)
C  AVERAGE FORBS OVER 2 RANGE SITES IN EACH PASTURE
      FA=(RA(II,1,4)+RA(II,2,4))/2.
      GA=0
C AVERAGE GRASSES OVER 2 RANGE SITES AND 3 PLANT GROUPS
      DO 634 K=5,7
      GA=GA+(RA(II,1,K)+RA(II,2,K))/6.
 634  CONTINUE
C  NOW AVERAGE OVER THE TIME PERIOD
      FJ1S1(I)=FJ1S1(I)+FA/13.
      GJ1S1(I)=GJ1S1(I)+GA/13.
 635  CONTINUE
 640  CONTINUE
      IF(IWEEK.GT.11)GOTO 650
C  AVERAGE % SHRUB COVER  MAR 1  MAY 31
      DO 645 I=1,ISAGE
      II=ISTRUT(I)
C  AVERAGE % COVER OVER 2 RANGE SITES
C  MARCH 15 TO MAY 31
      CO=(PC(II,1,2)+PC(II,2,2))/2.
```

```
C  AVERAGE OVER TIME PERIOD - 11 WEEKS
      CM1M31(I)=CM1M31(I)+CO/11.
  645 CONTINUE
  650 CONTINUE
C
C  AVERAGE FORBS,GRASSES AND % COVER  MAR 15  SEPT 30
      IF(IWEEK.GT.28)GOTO 660
      DO 655 I=1,ISAGE
      II=ISTRUT(I)
C  AVERAGE FORB DENSITY OVER 2 RANGE SITES
      FO=(RA(II,1,4)+RA(II,2,4))/2.
C  AVERAGE COVER OVER 2 RANGE SITES
      CO=(PC(II,1,2)+PC(II,2,2))/2.
      GA=0.
C  AVERAGE GRASSES OVER RANGE SITES AND 3 TYPES OF GRASS
      DO 654 K=5,7
      GA=GA+(RA(II,1,K)+RA(II,2,K))/6.
  654 CONTINUE
C  NOW AVERAGE OVER TIME PERIODS
      FM15S3(I)=FM15S3(I)+FO/28.
      CM15S3(I)=CM15S3(I)+CO/28.
      GM15S3(I)=GM15S3(I)+GA/28.
  655 CONTINUE
  660 CONTINUE
      IF(IWEEK.NE.37)GOTO 1000
C
C  NOW DETERMINE POPULATION DYNAMICS OVER LAST YEAR
C  CHICK NUMBERS  SEPT 31
C  FIRST NESTING SUCCESS BY STRUTTING GROUND
      DO 700 I=1,5
      TOT=FA1J15(I)+GA1J15(I)
      TT=0
      IF(TOT.GT.0)TT=FA1J15(I)/TOT
      ANEST(I)=SLP(TOT,ANX,ANY,3)
      IF(TT.LT..1)ANEST(I)=ANESMN
      YNEST(I)=SLP(TOT,YNX,YNY,3)
      IF(TT.LT..1)YNEST(I)=YNESMN
C
C  NOW CHICKS PER HEN
      TOT=FJ1S1(I)+GJ1S1(I)
      CHEN(I)=SLP(TOT,CHHX,CHY,3)
      TT=0
      IF(TOT.GT.0)TT=FJ1S1(I)/TOT
      IF(TT.LT..1)CHEN(I)=CHENMN
C  CALCULATE # OF CHICKS
      CHICK(I)=(ANEST(I)*AHEN(I)+YNEST(I)*YHEN(I))*CHEN(I)
  700 CONTINUE
C
C  DETERMINE HEN SURVIVAL  MAR 15  SEPT 30
C  OPTIMAL ACCORDING TO FORBS AND GRASSES @ 25% COVER
      DO 705 I=1,5
      TOT=FM15S3(I)+GM15S3(I)
      SURVH(I)=SLP(TOT,XHSUR,YHSUR,3)
C  MODIFY ACCORDING TO COVER
      FAC=SLP(CM15S3(I),XHFAC,YHFAC,4)
C  MALE  SURVIVAL
```

```
      SURVM(I)=SLP(CM1M31(I),XMSUR,YMSUR,5)
 705   CONTINUE
C
C  HUNT THE GROUSE - FALL POPULATION
      DO 706 I=1,5
      AHEN(I)=AHEN(I)*(1.-SHUNT)
      AMALE(I)=AMALE(I)*(1.-SHUNT)
      YHEN(I)=YHEN(I)*(1.-SHUNT)
      YMALE(I)=YMALE(I)*(1.-SHUNT)
 706  CONTINUE
C  CALCULATE NUMBER FOR EACH POPN SEPT 30 AND ADD RECRUITS
      XTT=TOTHEN+TOTMAL
      TOTHEN=0
      TOTMAL=0
      DO 710 I=1,5
      AHENF(I)=(AHEN(I)+YHEN(I))*SURVH(I)*FAC
      AMALEF(I)=(AMALE(I)+YMALE(I))*SURVM(I)
C
C  CALCULATE POP'N AFTER WINTER(MAR 15)
      AHEN(I)=AHENF(I)*WHENS
      AMALE(I)=AMALEF(I)*WMALES
      YHEN(I)=CHICK(I)*(1.-CMALE)*WHENS
      YMALE(I)=CHICK(I)*CMALE*WMALES
      TOTHEN=TOTHEN+AHEN(I)+YHEN(I)
      TOTMAL=TOTMAL+AMALE(I)+YMALE(I)
 710  CONTINUE
      SAGEG=TOTHEN+TOTMAL
 1000 CONTINUE
      RETURN
      END
```

3.2 DATA FILES

SAVAL.D

This is the main data file called by the initialization subroutine UINIT. Data files associated with each subroutine are attached to this file by the use of $CONTINUE statements. The data files are listed according to the order they appear in SAVAL.D.

```
 1      S GPLANT(ALL,ALL,ALL)=0.
 1.02   $CONTINUE WITH GROW.D RETURN
 1.05   $CONTINUE WITH CHOW.D RETURN
 1.1    S IBEEF=1
 1.2    S IWAT=1
 1.3    S IWILD=1
 1.4    S IVEG=1
 2      $CONTINUE WITH DAVE.DD RETURN
 3      S DPRECT(ALL)=0.
 4      S CU(ALL)=0.
 5      $CONTINUE WITH BEEF.D RETURN
 6      $CONTINUE WITH DAVE.D RETURN
 7      $CONTINUE WITH WILD.D2 RETURN
 8      $CONTINUE WITH WAT.D RETURN
 8.01   SAVE FILE=-S
 8.02   MACRO GO
 8.04   RUN 1 19
 8.06   SET #NYSKIP=38
 8.08   RUN 20 476
 8.1
 8.12   MACRO IRR
 8.14   S HAYOP(ALL)=2
 8.16   S ISTR=7
 8.18   S IENR=37
 8.2
 8.22   MACRO STOCKER
 8.24   S HAYOP(ALL)=3
 8.26   S IAHB=0
 8.28   S COW(ALL)=500 300 1
 8.3    AT 39 'S YRB=150'
 8.32   AT 77 'S YRB=300'
 8.34   AT 115 'S YRB=450'
 8.36   AT 153 'S YRB=600'
 8.38   AT 49 'S SHKILL(3)=0.6'
 8.385  AT 49 'S IVM=1'
 8.39   AT 50 'S IVM=0'
 8.4    AT 50 'S SHKILL(3)=0.0'
 8.42   AT 49 'S VMANIP(5,2,3)=2203'
 8.44   AT 50 'S VMANIP(5,2,3)=0'
 8.46   AT 49 'S VMANIP(7,2,3)=3568'
 8.48   AT 50 'S VMANIP(7,2,3)=0'
 8.53
 8.58   MACRO FIRE
```

```
     8.63   S IAHB=1
     8.68   AT 30 'S VMANIP(9,1,2)=2000'
     8.69   AT 30 'S IVM=1'
     8.7    AT 31 'S IVM=0'
     8.73   AT 30 'S SHKILL(3)=1.0'
     8.78   AT 31 'S VMANIP(9,1,2)=0.0'
     8.83   AT 31 'S SHKILL(3)=0.0'


    G R O W . D
    ===========

     1      S IGROW=0
     2      S EMP=.036155
     3      S EMNP=77.
     4      S FP1=2.2577
     5      S FP2=.2213
     6      S GENP1=2.54
     7      S GENP2=.0314
     8      S PM1=.077
     9      S PM2=.75
    10      S G1(ALL)=73.099 39.526
    11      S G2(ALL)=.002779 .003139
    12      S G3(ALL)=.02736 .0506
    13      S G4(ALL)=3.8538 2.2146

    C H O W . D
    ===========

     1      S WPREF(ALL)=2 1
     2      S RPREF(ALL)=1 2 3
     3      S FPREF(ALL)=0.1 .05 .05 .2 .3 .1 .2
     4      S ALPH(ALL)=126
     5      S IMUNCH=2

    D A V E . D D
    =============

     1      S IOC(ALL)=1 14*0
     2      S NRT=3
     3      S NPAS=9
     4      S RA(ALL,ALL,ALL)=0
     5      S CE(ALL,ALL,ALL)=0.
     6      S WE(ALL,ALL,ALL)=0.
     7      S FTOT(ALL)=4000 5000 8000
     8      SAVE FILE=-S

    B E E F . D
    ===========

     1      S COWW(ALL)=700 350 700
     1.1    S BUYHAY=2000.
     1.2    S IUSE=0
     1.5    S IECON=1
     2      S ISTOP=0
     3      S COWWMN=700.
```

```
S CE(ALL,ALL,ALL)=0
S YII=4.1
S SLI=.0136
S CALF=350.
S COW(ALL)=500 0 1
S IPYN(ALL)=7*1 2 2
S IGR(ALL)=2 2 8 4 3 1 9 6 5
S IPCNT(ALL)=7*1 2 2
S IPTO(ALL)=8 1 4 9 6 5 2 2 3
S IPW(ALL)=3 3 2 2 6 6 4 4 0
S IPREF(ALL)=5 6 7 2 1 4 3
S DPW=7
S IGRT=0
S IPAST(ALL)=1 2 3 6 4 5 7 9 8
S IWM=10
S YTDN(ALL)=.4
S SLTDN(ALL)=1.3
S YWG(ALL)=-1.0 0.0 0.5 0.7 0.9
S FTHR=50
S XCLF(ALL)=0 600 800 950 1050 2000
S YCLF(ALL)=0 0 .85 .85 .6 .6
S PCS=.8
S PAS=.08
S CALFW=60.
S HPC=.025
S DPWN=156
S IAHS=1
S IAHB=1
S XWNG(ALL)=0 22 100
S YWNG(ALL)=-1.5 0 5
S WGAR(1,ALL)=0
S WGAR(2,ALL)=100 0 .5 1. 1.5 1.8
S WGAR(3,ALL)=150 0 1. 1.5 2.5 2.7
S WGAR(4,ALL)=200 0 1.9 3.5 3.8 4.0
S WGAR(5,ALL)=250 0 2.3 3.9 4. 4.6
S WGAR(6,ALL)=300 0 2.6 4.5 4.7 5.2
S WGAR(7,ALL)=350 0 2.9 5.1 5.4 6.0
S WGAR(8,ALL)=999 0 4*1000
S TGWA=0.
S TGWAO=0.
S COWB=0.
S YRB=1.
S CLFB=0.
S PPCOW=.4
S PPCLF=.6
S PPYR=.63
S DGH=0.015
S DBH=46.
S FC=2.5E5
S VCC=60.
S DAW=5
S DSH=60.
S XM1=2.5
S XM2=.4
S XM3=.15
S CMIN(ALL)=700. 700.
```

```
S RA(1...5,ALL,9)=1.
S RA(1...5,ALL,10)=0.
S RA(6,ALL,9)=.5
S RA(6,ALL,10)=.5
S RA(7,ALL,9)=.65
S RA(7,ALL,10)=.35
S RA(8,ALL,9)=.8
S RA(8,ALL,10)=.2
S RA(9,ALL,9)=.65
S RA(9,ALL,10)=.35
S ISTR=5
S IENR=35
S YEARW=700.
S NPMAX=9
S COWMAX=1000.
S HPP(ALL)=5.
```

DAVE.D

```
S RQEVLB(ALL)=3*5 4*10 --- LB. OF WATER REQ./LB. OF NEW GROWTH
S ILUMP=0
S IVM=0 --- SWITCH FOR VEG. MANIP. NO IF =0.
S RANEW(ALL,ALL,ALL)=0.
S NEWRS(ALL,ALL)=0
S GSOXM(ALL,ALL)=0.
S PCMAX2(ALL,ALL)=0.
S PCMAX(ALL,ALL)=0.
S PWTMAX(ALL,ALL)=0.
S AWCNEW(ALL,ALL,ALL)=0.
S GSOXM(1,ALL)=16. 17. 21. 90. 100. --- CLAYPAN BARS TENSION
S GSOXM(2,ALL)=13. 18. 24. 90. 100. --- LOAMY
S GSOXM(3,ALL)=9. 12. 16. 90. 100. --- RIPARIAN
S PCMAX2(1,ALL)=30. 45. 15. 5. 5. --- CLAYPAN<% COVER
S PCMAX2(2,ALL)=35. 20. 30. 0. 15. --- LOAMY<OF SHRUB,BARE,
S PCMAX2(3,ALL)=25. 5. 60. 0. 10. --- RIP<GRASS,ROCK,LITTER
S PCMAX(1,ALL)=15. 30. 0. 30. 55. --- CLAYPAN <% COVER
S PCMAX(2,ALL)=30. 35. 0. 35. 80. --- LOAMY<OF GRASS,SHRUB,
S PCMAX(3,ALL)=60. 25. 0. 25. 95. --- RIP<TREE,CANOPY,GRND
S PWTMAX(1,ALL)=45. 50. --- CLAYPAN. WT. % OF SHRUBS
S PWTMAX(2,ALL)=65. 50. --- LOAMY. AND GRASSES
S PWTMAX(3,ALL)=70. 70. --- RIPARIAN
S NEWRS(1,1...3)=3 5 10 --- GROUPING OF OLD RANGE SITES
S NEWRS(2,1...5)=4 6 7 8 9
S NEWRS(3,1...2)=1 2
S PLNTMX(ALL)=3*10000. 4*2000.
S SPB=1.0  --- CONSTANT FOR SETTING INITIAL PLANT BIOMASS
S SPBEXP=1.0 --- EXPONENT FOR SETTING INITIAL PLANT BIOMASS
S AMEAD(ALL)=621. 829. 1225.
S HMMR=90.
S HAYP(ALL)=0.
S THAYP=0.
S ROOTMX(ALL)=3*1000. 400. 3*1000. --- MAX. ROOT STORAGE
S GMAX(ALL)=3*1.5 4*3
S GTEMPX(ALL)=40. 80. 100.
S GTEMPY(ALL)=0. 0.3 0.25 --- TEMPERATURE LIMITATION
```

```
 37      S GSOY(ALL)=0. 0.2 1. 1. 0.5 --- MOISTURE LIMITATION
 38      S PMY(ALL)=0.01 0. --- % MORTALITY WITH LOW GROWTH
 39      S PMX(ALL)=0. 0.05
 40      S SPB=0.1 --- SPRING PLANT BIOMASS (INITIAL)/PRODN.
 41      S CWST=0.1 --- COW WASTAGE
 43      S REQGA=0.01 --- %GROWTH REQUIRED AFTER FLOWERING
 44      S IFDATE=19 --- WEEK OF FLOWERING
 45      S PSTR=0.1 --- % OF SHOOT BIOMASS SENT TO ROOTS
 46      S PRTS=0.1 --- % OF ROOT BIOMASS TO SHOOTS/WEEK
 47      S RWS=0.7 --- SURVIVAL OF ROOT POTENTIAL BIOMASS OVER WINTER.
 48      S PWS(ALL)=6*0.2 0.05 --- PLANT WINTER SURVIVAL
 49      S HAYY(1,ALL)=0. 1. 1.25 1. 0.5
 50      S HAYY(2,ALL)=0. 1.5 1.75
 51      S HAYY(3,ALL)=0. 2. 2.5
 52      S HX(ALL)=0. 2. 3. 5. 6.
 53      S VSEED(ALL)=0. 90. 90. 30. 800. 10. 2.
 54      S HAYOP(ALL)=1. 1. 1. --- 1=POOR IRR.,2=GOOD. IRR,3=FERT
 55      S ER(ALL)=0.34 0.36 0.38
 56      S SVPX(ALL)=1. 38.
 57      S SVPY(ALL)=15. 10. --- SHRUB % PROTEIN
 58      S PVPX(ALL)=1. 38. --- PERRENNIAL GRASSES  FORBS
 59      S PVPY(ALL)=15. 3.
 60      S CVPX(ALL)=1. 10. ---  YOUR CHEATIN' GRASS...
 61      S CVPY(ALL)=15. 0.
 62      S VMANIP(ALL,ALL,ALL)=0.
 63      S SHKILL(ALL)=3*0.8 1.0
 64      S PAST(1...6)=1911. 1564. 3139. 3464. 4372. 4698. 6448.
 65      S PAST(7...13)=5803. 9902. 2059. 2669. 1225. 1809.
 66      S RPB=10. --- ROOTS/ABOVE GROUND AT START
 67      S RLP=1.4 --- (GRASS+LITTER)/GRASS
 68      S PC(ALL,ALL,ALL)=0.
 69      MACRO WDARLING
 70      PRINT RA(1,2,1) RA(1,2,2) RA(1,2,4) RA(1,2,5) RA(1,2,6) RA(1,2,7)
 71
 72      $CONTINUE WITH DAVE.SET RETURN
DAVE.SET:

  1      S RA(1,1,1...8)=    0.   19.   16.    3.   79.    1.    0.  933.
  2      S AWCNEW(1,1,ALL)= 0.13 0.13 0.08
  3      S RA(1,2,1...8)=    0.   19.   16.    3.   79.    1.    0.  933.
  4      S AWCNEW(1,2,ALL)= 0.14 0.11 0.08
  5      S RA(1,3,1...8)=    2.   42.   43.  134.    5.  150.    5.   45.
  6      S AWCNEW(1,3,ALL)= 0.15 0.15 0.14
  7      S RA(2,1,1...8)=    0.   19.   16.    3.   79.    1.    0.  782.
  8      S AWCNEW(2,1,ALL)= 0.13 0.13 0.08
  9      S RA(2,2,1...8)=    0.   19.   16.    3.   79.    1.    0.  782.
 10      S AWCNEW(2,2,ALL)= 0.14 0.11 0.08
 11      S RA(2,3,1...8)=    0.    0.    0.    0.    0.    0.    0.    0.
 12      S AWCNEW(2,3,ALL)= 0.0  0.0  0.0
 13      S RA(3,1,1...8)=    0.    8.    2.   11.    1.    8.    0.  470.
 14      S AWCNEW(3,1,ALL)= 0.13 0.13 0.08
 15      S RA(3,2,1...8)=    0.   21.    7.   11.    3.    5.    4. 2653.
 16      S AWCNEW(3,2,ALL)= 0.14 0.11 0.08
 17      S RA(3,3,1...8)=    0.    0.  468.   86.    0.  192.    0.   16.
 18      S AWCNEW(3,3,ALL)= 0.16 0.16 0.16
 19      S RA(4,1,1...8)=    0.    8.    2.   11.    1.    8.    0. 1113.
```

```
S AWCNEW(4,1,ALL)= 0.13 0.13 0.08
S RA(4,2,1...8)=    0.   33.   11.   14.    6.    6.    3. 2230.
S AWCNEW(4,2,ALL)= 0.14 0.12 0.09
S RA(4,3,1...8)=    6.  146.    2.   51.   19.   14.   18.  121.
S AWCNEW(4,3,ALL)= 0.13 0.13 0.10
S RA(5,1,1...8)=    0.    9.    3.   12.    2.    8.    0. 1961.
S AWCNEW(5,1,ALL)= 0.13 0.13 0.08
S RA(5,2,1...8)=    2.   51.   17.   17.   10.    6.    4. 2203.
S AWCNEW(5,2,ALL)= 0.14 0.12 0.09
S RA(5,3,1...8)=    0.  198.  119.   56.   12.   45.    9.  208.
S AWCNEW(5,3,ALL)= 0.13 0.13 0.11
S RA(6,1,1...8)=    0.    8.    2.   11.    1.    8.    0.  693.
S AWCNEW(6,1,ALL)= 0.13 0.13 0.08
S RA(6,2,1...8)=    0.    0.    0.    0.   80.    0.    0. 3703.
S AWCNEW(6,2,ALL)= 0.14 0.11 0.08
S RA(6,3,1...8)=    6.  139.   25.   52.   18.   23.   17.  302.
S AWCNEW(6,3,ALL)= 0.13 0.13 0.10
S RA(7,1,1...8)=    0.    9.    2.   11.    2.    8.    0. 2357.
S AWCNEW(7,1,ALL)= 0.13 0.13 0.08
S RA(7,2,1...8)=    1.   43.   16.   15.    6.    6.    5. 3568.
S AWCNEW(7,2,ALL)= 0.14 0.12 0.09
S RA(7,3,1...8)=    6.  145.    2.   51.   18.   15.   17.  523.
S AWCNEW(7,3,ALL)= 0.13 0.13 0.10
S RA(8,1,1...8)=    2.   28.   14.   18.   11.    4.    1. 3713.
S AWCNEW(8,1,ALL)= 0.08 0.08 0.01
S RA(8,2,1...8)=    0.   15.   48.   57.    7.    5.    0. 1984.
S AWCNEW(8,2,ALL)= 0.15 0.14 0.11
S RA(8,3,1...8)=    1.   29.    0.   46.   13.  141.    4.  106.
S AWCNEW(8,3,ALL)= 0.15 0.15 0.15
S RA(9,1,1...8)=    3.   29.   14.   19.   11.    4.    1. 6250.
S AWCNEW(9,1,ALL)= 0.08 0.08 0.02
S RA(9,2,1...8)=    6.   31.   30.   31.    7.   15.    2. 3495.
S AWCNEW(9,2,ALL)= 0.14 0.11 0.09
S RA(9,3,1...8)=    2.   36.  153.  118.    6.  173.    7.  157.
S AWCNEW(9,3,ALL)= 0.15 0.15 0.15


W I L D . D 2
=============

S NPERP(ALL)=5 3 5 --- NUMBER OF PASTURES UTILIZED BY DEER IN 3 PER
IODS
S NPASD(1,ALL)=3 4 5 6 7 --- PASTURES USED BY DEER IN PERIOD 1
S NPASD(2,ALL)=5 7 13 --- DITTO PERIOD 2
S NPASD(3,ALL)=5 7 8 9 13--- DITTO PERIOD 3
S NPERT(ALL)=2 2 3 --- NUMBER OF RANGE SITES USED BY DEER IN 3 PERI
ODS
S NTYPE(1,ALL)=2 3--- RANGES SITES USED PERIOD 1
S NTYPE(2,ALL)=2 3--- RANGE SITES IN PERIOD 2
S NTYPE(3,ALL)=1 2 3 --- RANGE SITES USED IN PERIOD 3
S PREF(1,ALL)=3*.1 6*5.--- PREFERENCE PARAMETERS FOR PLANT GROUP1 B
Y MONTH
S PREF(2,ALL)=3*.2 3*10 3*2
S PREF(3,ALL)=3*.2 4*.01 2*.2
S PREF(4,ALL)=9*20.
S PREF(5,ALL)=.01 10 10 .01
```

```
14     S PREF(6,ALL)=.01 2*10 .01
15     S PREF(7,ALL)=.01 2*20 .01
16     S DINGW(ALL)=12.4 20.2  ---  IB/WEEK ING FAWN AND ADULT
17     S FLEAVE(ALL)=1.  --- AMOUNT OF FORAGE NOT EATEN
18     S DFEM=150  INITIAL NUMBER OF FEMALE ADULT DEER
19     S DMALE=100   INITIAL NUMBER OF MALE ADULT DEER
20     S FAWN=50   INITIAL NUMBER OF FAWNS
21     S CAL(1,ALL)=.55 .64 .73 .86--- NUTRITIONAL VALUE FOR EACH PLANT TY
       PE BY MONTH
22     S CAL(2,ALL)=.86 1.0
29     S FNEED=18       """"""""""FAWN
30     S XMALED(ALL)=0 1
31     S YMALED(ALL)=0 .95  --- MALE WINTER SURVIVAL AS FUNCTION OF HEALTH
        INDEX
32     S XFEM(ALL)=0 1
33     S YFEM(ALL)=0 .8   ---  FEMALE WINTER SURVIVAL AS FUNCTION OF HEALT
       H INDEX.
34     S XFNY(ALL)=0 1
35     S YFNY(ALL)=0. .8   ----  FAWN WINTER SURVIVAL AS FUNCTION OF HEALT
       H INDEX.
36     S FPERC=.4    PROP'N OF FAWNS  THAT ARE MALE
37     S HFRAC=.25  PROPORTION OF GMU COVERED BY SAVAL PROJECT AREA
38     S SHUNT=.1   PROPORTION OF SAGE GROUSE POPULATION REMOVED IN FALL B
       Y HUNTING
39     S FRAC=.25   FRACTION OF DEER POPULATION OVERWINTERING EAST OF SAVA
       L PROJECT
40     S PERMIT=500   # DEER HUNTING PERMITS IN GMU
41     S DAYH=4   # DAYS/HUNTER/YEAR
42     S HHX(ALL)=0 46 1000 --- DENSITY OF BUCKS ON RANGE FOR SLP FUNCTION
43     S HHY(ALL)= 0 .4 1   ---  DEER HUNTING SUCCESS PER UNIT OF EFFORT -
        HUNTER DAYS
44     S XFAW(ALL)=0 1
45     S YFAW(ALL)=0 1.2--- # FAWNS/FEMALE AS FUNCTION OF HEALTH INDEX
46     S ISTRUT(ALL)=6 7 7 5 4  --- PASTURES CONTAINING SAGE GROUSE STUTTI
       NG GROUNDS
47     S ISAGE=5  NUMBER IDENTIFIED SAGE GROUSE POPULATIONS IN MODEL
48     S ANX(ALL)=0 150 500
49     S ANY(ALL)= 0 .35 .8  --- ADULT NESTING SUCCESS AS FUNCTION OF FORB
       S+GRASSES AVERAGE DENSITY
50     S YNX(ALL)= 0 150 500
51     S YNY(ALL)=0 .2 .65  ---  YEARLING NESTING SUCCESS AS FUNCTION OF F
       ORBS+GRASSES AVERAGE DENSITY;
52     S ANESMN=0  MINIMUM ADULT NESTING SUCCESS IF FORBS DENSITY TOO LOW
53     S YNESMN=0  MINIMUM YEARLING NESTING SUCCESS IF FORBS DENSITY TOO L
       OW;
54     S CHX(ALL)= 0 100 500  --- CHICKS/HEN
55     S CHY(ALL)=0 1 5--- NUMBER OF CHICKS PER HEN AS FUNCTION OF AVERAGE
        FORBS+GRASSES DENSITY
56     S CHENMN=0    MIN CHICKS/NEST
57     S AHEN(ALL)=2 1 8 6 38  ---INITIAL CONDITIONS ADULT HENS ON STUTTIN
       G GROUNDS FOR 5 IDENTIFIED POPULATIONS
58     S AMALE(ALL)=8 14 53 19 170  --- INITIAL CONDITIONSS ADULT MALES ON
        STRUTTING GROUNDS FOR 5 IDENTIFIED POPULATIONS
59     S YHEN(ALL)=1 1 4 3 15  --- INITIAL CONDITIONS YEARLING HENS ON 5 I
       DENTIFIED POPULATIONS
60     S YMALE(ALL)=4 7 25 9 75  --- INITIAL CONDITIONS  YEARLING MALES ON
```

```
          5 IDENTIFIED POPULATIONS
    61      S XHSUR(ALL)=0 100 500  ---  HEN SEASON SURVIVAL
    62      S YHSUR(ALL)=.6 .6 .9  --- HEN SURVIVAL OVER MARCH 15 TO SEPT 30 AS
             FUNCTION OF FORBS+GRASSES
    63      S XHFAC(ALL)=0 5 25 50
    64      S YHFAC(ALL)=.25 .25 1 .5 --- HEN SURVIVAL MODIFICATION FACTOR AS F
            UNCTION OF SHRUB COVER
    65      S XMSUR(ALL)=0 5 15 30 50
    66      S YMSUR(ALL)=.35 .35 .65 .65 .5 --- MALE SURVIVAL MARCH 15 TO SEPT
            30 AS FUNCTION OF % SHRUB COVER
    67      S WHENS=.9  OVERWINTER SURVIVAL RATE FOR HENS
    68      S WMALES=.8  OVERWINTER SURVIVAL RATE FOR MALES
    69      S DENERF=1E3  INITIAL CONDITION - KCAL 10**3 INGESTED BY FAWN DEER
            IN PREVIOUS YEAR
    70      S DENERA=1E3  INITAL CONDITION - KCAL 10**3 INGESTED BY ADULT DEER
            IN PREVIOUS YEAR
    71      S PERIN(ALL,ALL,ALL)=0--- INITIAL COND'N - PROP'N OF EACH PLANT TYP
            E IN DEER DIET BY PASTURE AND RANGE TYPE
    72      S WE(ALL,ALL,ALL)=0 --- POUNDS/ACRE OF EACH PLANT TYPE INGESTED BY
            DEER EACH WEEK BY PASTURE AND RANGE SITE
    73      S RRA(ALL,ALL,ALL)=0 --- DUMMY VARIABLE TO REFLECT DENSITY OF PLANT
            S AFTER REMOVING CATTLE GRAZING - OTHER WISE SAME AS RA
    74      S FK=4000  HALF SATURATION PARAMETER IN EXTRA MORTALITY FUNCTION AP
            PLIED TO FAWN DEER
    75      S CMALE=.4  PROPORTION OF SAGE GROUSE THAT ARE MALE IN FALL
    76      S SK=5000  HALF SATURATION PARAMETER IN EXTRA MORTALITY FUNCTION AP
            PLIED TO SAGE GROUSE
    77      S TOTHEN=0  TOTAL NUMBER OF SAGE GROUSE HENS MARCH 15
    78      S TOTMAL=0  TOTAL NUMBER OF MALE SAGE GROUSE MARCH 15
    79      S SAGEG =0  TOTAL NUMBER OF SAGE GROUSE ON SAVAL RANGE MARCH 15;
```

WAT.D

```
=========

 1.2    SET XLS(ALL)=4.5 2.8 0.16 0.
 2      SET LUPTR(1...12) = 7*0 2*1 0
 3      SET OAR = 2.07
 4      SET OCN = 80
 5      SET CNA(1...3) = 83 87 91
 6      SET CNB(1...3) = 0.28 0.18 0.13
 7      SET IPTR(1...10) = 2 3 3 2 3 2 2 1 1 2
 8      SET WATRES(1...3) = 10. 10. 20.
 9      SET PMECH = 1
10      SET FLFUDG = 1.
10.2    SET SOFDG = 1.
10.4    SET RFUDG = 1.
11      SET ARMAH(1...10)=0 0.1 0 0 1.34 0 0 0.63 0.85 1.27
12      SET ARGNC(1...10)=0 0.16 0 0 1.97 0 0 1.66 0.64 2.19
12.05   SET ARMAH(ALL)=2.62 1.48 0.1 0.
12.1    SET ARGNC(ALL)=4.16 2.30 0.16 0.
12.2    SET RUNOFF(ALL,ALL) = 0.
12.4    SET SOILOF(ALL,ALL) = 0.
13      SET SEDDEL = 0.2
14      SET CATFAC = 0.002
15      SET BSTB1 = 1
```

```
16      SET BSTB2 = 0.2
17      SET CUFS = 27
18      SET AFCON = 2
19      SET NSTEP = 0
20      SET JDAY = 65
21      SET WINDAY = 106
22      SET NWEEKS = 37
22.2    SET SNOPAC(ALL,ALL) = 0.
22.4    SET FREZDP(ALL,ALL) = 0.
22.6    SET SOWAT(ALL,ALL,ALL) = 0.
23      SET NFFLOW(1...12)=15 18 18 22 28 32 32 38 43 36 35 30
24      SET NFFLOW(13...38)=28 23 18 10 8 5 3 2 2 2 2 2 0
25      SET PMULT = 2.3
25.05   SET RM(ALL) = 0.
25.1    SET RM(9) = 12.
25.2    SET TMULT = 0.85
25.4    SET TSEDG = 0.
25.6    SET TSEDM = 0.
25.7    SET FTOT(ALL) = 0.
25.8    S TCOF = 0.42
26      S PREC(1...22)=0. 0. 0.2 0.12 12*0. 0.1 0.12 0.01 3*0.
27      S PREC(23...64)=0.15 0.3 0.5 26*0. 0.4 0.7 11*0.
28      S PREC(65...82)=0.05 0.04 4*0. 0.01 0.09 0.16 6*0. 0.1 0. 0.
29      S PREC(83...104)=0.22 0.09 0.04 16*0. 0.04 0.09 0.22
30      S PREC(105...120)=0. 0. 0.1 7*0. 0.16 0.09 0.01 3*0.
31      S PREC(121...142)=0.04 0.05 0. 11*0. 0.4 0.1 0.22 0. 0. 0.14 0.16
32      S PREC(143...181)=7*0. 0.08 8*0. 2*0.1 6*0. 0.02 0.04 0.14 12*0.
33      S PREC(182...210)=2*0.1 3*0. 0.02 18*0. 0.14 0.04 0.1 0. 0.1
34      S PREC(211...254)=31*0. 0.4 12*0.
35      S PREC(255...296)=0.1 8*0. 0.1 0.18 10*0. 0.02 4*0. 2*0.1 14*0.
36      S PREC(297...319)=0. .14 0.04 0.02 6*0. 2*0.1 11*0.
37      S PREC(320...333)=0.04 0.09 0.22 0. 0.1 6*0. 0.16 0.09 0.01
38      S PREC(334...365)=4*0. 0.04 0.05 22*0. 0.7 0.4 2*0.
39      S TMAXL(1...10)=36 40 40 42 41 34 31 38 33 27
40      S TMAXL(11...20)=17 30 42 37 40 39 32 20 24 33
41      S TMAXL(21...30)=35 30 40 45 35 31 23 24 24 21
42      S TMAXL(31...40)=27 40 42 44 44 42 42 31 38 38
43      S TMAXL(41...50)=41 44 42 41 42 38 38 40 43 37
44      S TMAXL(51...60)=35 37 35 39 44 49 52 55 44 43
45      S TMAXL(61...70)=42 38 38 39 33 36 36 39 42 46
46      S TMAXL(71...80)=37 30 41 48 34 29 46 35 37 47
47      S TMAXL(81...90)=32 39 38 33 37 38 28 39 49 26
48      S TMAXL(91...100)=31 36 38 43 50 37 37 38 41 43
49      S TMAXL(101...110)=40 45 49 54 62 56 65 70 69 72
50      S TMAXL(111...120)=74 67 59 54 45 53 64 67 67 60
51      S TMAXL(121...130)=53 58 65 64 64 69 60 59 55 45
52      S TMAXL(131...140)=43 48 51 56 55 55 43 59 65 69
53      S TMAXL(141...150)=75 73 71 40 35 39 47 57 57 54
54      S TMAXL(151...160)=55 51 51 40 50 50 52 55 66 74
55      S TMAXL(161...170)=75 73 68 60 62 56 57 71 81 79
56      S TMAXL(171...180)=78 80 78 76 64 76 76 70 70 80
57      S TMAXL(181...190)=81 67 67 72 72 77 77 80 79 79
58      S TMAXL(191...299)=83 79 84 79 76 77 82 88 82 86
59      S TMAXL(201...210)=82 85 92 94 93 90 90 93 92 93
60      S TMAXL(211...220)=85 86 84 85 88 76 82 85 84 81
61      S TMAXL(221...230)=86 82 86 89 87 88 85 67 77 81
```

```
  62      S TMAXL(231...240)=64 64 76 82 80 80 79 79 82 75
  63      S TMAXL(241...250)=75 71 63 68 76 79 78 85 85 81
  64      S TMAXL(251...260)=62 72 69 52 64 68 67 70 74 75
  65      S TMAXL(261...270)=80 75 63 62 56 67 69 71 76 77
  66      S TMAXL(271...280)=78 72 77 82 79 77 81 79 76 79
  67      S TMAXL(281...290)=78 78 75 77 69 55 52 40 36 38
  68      S TMAXL(291...300)=56 59 61 60 62 53 52 63 51 40
  69      S TMAXL(301...310)=38 50 57 62 64 58 59 65 67 69
  70      S TMAXL(311...320)=62 65  49 47 55 36 37 38 37 35
  71      S TMAXL(321...330)=38 47 40 42 42 41 33 30 26 41
  72      S TMAXL(331...340)=41 42 48 49 41 35 45 46 35 26
  73      S TMAXL(341...350)=25 17 27 33 34 44 46 46 46 48
  74      S TMAXL(351...360)=52 51 41 48 42 38 41 40 43 43
  75      S TMAXL(361...365)=49 59 49 48 51
  76      S TMINL(1...10)=15 8 16 9 24 21 16 26 27  12
  77      S TMINL(11...20)=11 11 30 31 27 25 18 11 -3 -7
  78      S TMINL(21...30)=4 6 2 7 8 2 -1 -5 -13 -16
  79      S TMINL(31...40)=-8 12 10 26 16 15 25 17 14 5
  80      S TMINL(41...50)=11 13 25 24 28 27 24 28 30 30
  81      S TMINL(51...60)=20 21 18 15 12 23 30 27 28 22
  82      S TMINL(61...70)=20 28 29 27 23 20 20 20 22 20
  83      S TMINL(71...80)=19 13 23 27 12  8 12 22 18 17
  85      S TMINL(81...90)=21 23 22 14 13  8 18 13 16 12
  86      S TMINL(91...100)=12 20 14 17 25 24 20 12 16 17
  87      S TMINL(101...110)=22 24 25 28 31 26 19 27 29 28
  88      S TMINL(111...120)=31 35 39 35 29 25 28 35 34 30
  89      S TMINL(121...130)=23 38 32 38 35 34 38 37 33 30
  90      S TMINL(131...140)= 30 29 28 32 36 32 25 32 33
  91      S TMINL(141...150)=36 43 39 30 27 28 30 27 29 34
  92      S TMINL(151...160)=36 38 31 32 30 30 33 29 32 37
  93      S TMINL(161...170)=40 42 42 34 32 31 34 37 42 45
  94      S TMINL(171...180)=40 46 40 38 39 32 39 39 27 37
  95      S TMINL(181...190)=44 50 51 46 44 38 37 36 45 43
  96      S TMINL(191...200)=41 42 38 42 43 37 41 2 48 41
  97      S TMINL(201...210)=41 45 48 53 51 49 46 47 48 49
  98      S TMINL(211...220)=53 48 51 49 41 51 33 40 47 44
  99      S TMINL(221...230)=45 42 38 40 45 43 45 48 33 40
 100      S TMINL(231...240)=35 35 31 37 43 38 39 39 40 45
 101      S TMINL(241...250)=34 36 41 35 31 36 38 38 41 50
 102      S TMINL(251...260)=41 33 41 44 40 32 42 36 36 36
 103      S TMINL(261...270)=35 42 34 29 27 21 26 27 29 33
 104      S TMINL(271...280)=34 42 31 35 41 31 33 33 34 35
 105      S TMINL(281...290)=32 31 40 33 33 29 19 22 26 26
 106      S TMINL(291...300)=24 23 25 22 23 20  7 14 25 26
 107      S TMINL(301...310)=23 16 11 16 24 23 30 31 26 25
 108      S TMINL(311...320)=31 33 25 28 34 31 25 21  2 11
 109      S TMINL(321...330)= 3  5  8 12  7  6 26 19  1 -3
 111      S TMINL(331...340)= 5 21 30 20  9 31 30 11  6 8
 112      S TMINL(341...350)= 8 1 -8 -2 -4  2  4 0 -1 19
 113      S TMINL(351...360)=22 20 20 20 18 19 28 23 20 29
 114      S TMINL(361...365)=23 26 25 19 20
```

3.3 COMMON BLOCK

SAVAL.C

This is the main common block, which is called by the initialization routine UINIT. Common block files associated with subroutines are attached to SAVAL.C by means of $CONTINUE statements; these files are listed according to their order of occurrence in SAVAL.C.

```
$CONTINUE WITH DAVE.C RETURN
$CONTINUE WITH BEEF.C RETURN
$CONTINUE WITH WAT.C RETURN
$CONTINUE WITH WILD.C2 RETURN
      COMMON IWEEK,IMONTH
      COMMON IVEG,IWILD,IWAT,IBEEF
$CONTINUE WITH CHOW.C RETURN
$CONTINUE WITH GROW.C RETURN
```

DAVE.C

```
      COMMON GCOMP(9,3,7)
      COMMON RANEW(9,3,14)
      COMMON TOTPB(9,3),POTG,RQEVIN,AVEVIN,RQEVLB(7)
      COMMON I,IP,J,K
      COMMON AWCNEW(9,3,3),IVM
      COMMON ILUMP
      COMMON NRT,NPAS,IOC(15),AMEAD(3),HMMR,PLNTMX(7)
      COMMON NEWRS(10,10),SPBEXP
      COMMON GMRED(9,3,7),GPCWT(13,7),ROOTMX(7)
      COMMON RPB,RLP
      COMMON AWC(10,3),RA(9,3,14),SPB,ROOT(9,3,7)
      COMMON VMANIP(9,3,4),PAST(13),SHKILL(4),PREM
      COMMON ARET,VSEED(7),THAYP,HY(5),HAYY(3,5),HX(5)
      COMMON HAYOP(3),WPA(3),HAYP(3),PSTR,PRTS,RWS
      COMMON TPROD(13,7),TRED,REQGB,REQGA,IFDATE
      COMMON GTEMPX(3),GTEMPY(3),WMAX,GPLANT(9,3,7)
      COMMON GMAX(7),GSOX(5),GSOXM(10,5),GSOY(5)
      COMMON PMR,PMX(2),PMY(2),CWST,DROOT,DPB
      COMMON PNGR,PWS(7),PTOT,PCWT(9,3,7),VP(7)
      COMMON SVPX(2),SVPY(2),PVPX(2),PVPY(2),CVPX(2)
      COMMON CVPY(2),PC(9,3,5),PWTMAX(10,2),PCMAX(10,5)
      COMMON PCMAX2(10,5),TOTPCT,ER(10),GTPROD(13)
```

BEEF.C

```
      COMMON COW(3),COWW(3),CALFW,HAYB,HAYS,HAYT
      COMMON IYPN(9),IPTO(9),IPCNT(9),IGR(9),IPW(9),IPREF(7)
      COMMON DFW,YII,SLI,TTREQ,TREQ(3),IGRT,IPAST(9),IUSE
      COMMON IWM,CE(9,3,7),BEAT(3),YTDN(7),SLTDN(7)
      COMMON YWG(5),WGAIN(3),FLEFT,FOLD,FSTART,FTHR
```

```
        COMMON XCLF(6),YCLF(6),CALF,PCS,PAS,HPC,DPWN,IAHS
        COMMON IAHB,HAYR(3),THAYR,XWNG(3),YWNG(3)
        COMMON TDN(3),XWG(5),IPYN(9),WGAR(8,6)
        COMMON CALFS,COWS,YEARS,PPCOW,PPCLF,PPYR
        COMMON COSTS,DGH,FC,VCC,DAW,TGWA,TGWAO
        COMMON REV,DSH,RNP,GVO,XM1,CVA,XM2,RNA,XM3
        COMMON BEEF,PCALF
        COMMON YRB,CLFB,COWB,DBH
        COMMON NPAST
        COMMON YEARW,NPMAX,CU(9),COWMAX,HPF(3),CMIN(3),THAYG
        COMMON IENR,ISTR
        COMMON COWWMN,ISTOP,IECON,PBSLD
        COMMON BUYHAY
```

```
W A T . C
=========
```

```
        COMMON  PREC(365), XLS(10)
        COMMON  TMAXL(365), TMINL(365), CNA(3), CNB(3)
        COMMON  SNOPAC(9,3),DPREC(13), DPRECT(13), SOWAT(9,3,3)
        COMMON WATRES(3), SOILOF(9,3), RUNOFF(9,3)
        COMMON  ARMAH(10), ARGNC(10), FTOT(3), FMIN(3), NFFLOW(38)
        COMMON  WTWOOD, BSTAB, BSTB1, BSTB2, TMAX(13)
        COMMON  OCN, OAR, PMULT, TMULT, FLFUDG, ORUN
        COMMON  UEGNC, UEMAH, CATFAC, BETOT, WATQAL, WQUAL
        COMMON  CUFS, AFCON, IPAS, IRTYPE, RADLAN, ETPOT
        COMMON  PACAN, ETPLNT,ETSOIL, ILEAK, IFIL, APAR, BPAR
        COMMON  S, SMELT, DMTEMP, WATIN, RFAC, CFAC
        COMMON  FLGNC, FLMAH, OS, RM(13)
        COMMON  PCDUM, PCDUM1, PCDUM2, FREZDP(9,3)
        COMMON SEDDEL, PMECH, WINDAY, NWEEKS
        COMMON SO(9,3,3)
        COMMON  NSTEP, JDAY, NDAYS, IWFLG,  IDAY
        COMMON  LUPTR(13), IPTR(10)
        COMMON  SOFDG, FWTOT(3)
        COMMON PRECIP(13), RFUDG, TSEDG, TSEDM
        COMMON  PEVAP(9,3), ETPREM, TCOF, ETSUM
```

```
W I L D . C 2
=============
```

```
        COMMON HEALA,HEALF,DENERA,DENERF,ANEED,DEER,FNEED,DMALE
        COMMON XMALED(2),YMALED(2),DFEM,XFEM(2),YFEM(2),FAWN,XFNY(2)
        COMMON ITRIG(3),FPERC,YFNY(2)
        COMMON IC(3),DSEAS,FRAC,HDAYS,HFRAC,PERMIT,DAYH,KILL
        COMMON HHX(3),HHY(3),TKILL,XFAW(2),YFAW(2),IFLAG,TOTIN,NPERP(
  3)
        COMMON NPASD(3,13)
        COMMON NPERT(3),NTYPE(3,10),RRA(13,3,7),TOTVEG,PREF(7,12)
        COMMON PERIN(13,3,7),TDEMDA,DINGW(2),TDEMDF
        COMMON FLEAVE(7),CAL(7,12)
        COMMON ISTRUT(5),FA1J15(5),FJ1S1(5),GJ1S1(5),CM1M31(5)
        COMMON FM15S3(5),CM15S3(5),GM15S3(5),ANX(3),ANY(3),ANEST(5),A
  NESMN
```

```
      COMMON YNEST(5),YNX(3),YNY(3),CHEN(5),CHX(3),CHY(3),CHENMN
      COMMON CHICK(5),AHEN(5),YHEN(5),SURVH(5),XHSURR(3),YHSUR(3),FA
C
      COMMON XHFAC(4),YHFAC(4),SURVM(5),XMSUR(5),YMSUR(5),AHENF(5)
      COMMON AMALE(5),YMALE(5),WHENS,WMALES,CMALE,YNESMN,SAGEG
      COMMON TOTHEN,TOTMAL
      COMMON GA1J15(5),AMALEF(5),SK,XMFAW,FK
      COMMON WE(13,3,7),SHUNT,ISAGE,TDEER
```

CHOW.C

```
===========

      COMMON H(3),ALPH(3),PREFF(7,3,2),TTAT(3,7,3,2),TDIE(7,3,2)
      COMMON TPREF,FPREF(7),WPREF(2),RPREF(3)
      COMMON IMUNCH
```

GROW.C

```
===========

      COMMON EM,EMP,EMN,EMNP,GEN,GENP1,GENP2,FP1,FP2
      COMMON REMN,PM1,PM2,RIN,SURP,DNEG,G1(2),G2(2),G3(2),G4(2),IGR
OW
```

II. Integrated Sage Grouse/Walker Vegetation Model

1. INTRODUCTION

Following the first Saval workshop in November, 1981, it was recognized that there was a need for a less complex model of key system interactions. Therefore, a simple model was constructed to simulated interactions between grazing, vegetation, and sage grouse on an APPLE microcomputer. The rules for grazing and vegetation dynamics are drawn from Walker et al. (1981), which is included here to facilitate understanding of the program listing. The program is included on the diskette at the back of this report.

The model runs on an annual time step, tracking changes in the numbers of sage grouse (adult hens and males), shrub biomass and growth rate, grass biomass and growth rate, grass consumption by herbivores, and the infiltration rate of water into the soil.

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STABILITY OF SEMI-ARID SAVANNA GRAZING SYSTEMS

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SUMMARY

(1) Semi-arid savannas, wherever they occur, have generally been overgrazed and encroached on by bush. A model is developed which accounts for the growth of woody vegetation and of grasses, and analyses the competition between them for available soil water.

(2) The model is based on Walter's two layer hypothesis. Woody vegetation and grasses compete for water in the surface layers of the soil, but woody vegetation has exclusive access to a source of water relatively deep underground. Where there is only a small biomass of grass the soil surface tends to become impermeable and, in these conditions, the model shows that two different steady states may develop: with a lot of woody vegetation alone, or with a relatively large biomass of grass and rather little woody vegetation.

(3) The results are discussed in terms of the concept of resilience. The continued existence of both stable states under ranching conditions seems to depend on periodic heavy, or over-, grazing which allows for the maintenance of unpalatable or unstable grass species, which thus set a minimum to grass biomass—a minimum which cannot be reduced by herbivores.

(4) Comparison of the dynamics of various savanna and other natural systems leads to the conclusion that the resilience of the systems decreases as their stability (usually induced) increases.

INTRODUCTION

In this paper the term 'semi-arid savanna' refers to those regions of the world, which, in their natural state, have a predominant continuous grass cover, with scattered to numerous trees and shrubs. Plant growth is water-limited. The term does not include those areas that would develop into woodland in the absence of fire or other disturbance.

A series of radical changes occurred in these semi-arid savannas, beginning in the late 1800s when settlement of the drier parts of the tropics and sub-tropics by Europeans was at its peak. These changes have continued and show a remarkable similarity wherever semi-arid savanna is found. The general pattern of events was initiated by the introduction of domestic cattle or sheep, or both, and resulted in a drastic reduction in numbers, or even elimination, of indigenous large mammalian herbivores and their predators.

The populations of cattle and sheep increased rapidly, exceeded the carrying capacity of the vegetation, showed increased mortality (usually in conjunction with a period of drought), and crashed. They then recovered somewhat, and fluctuated around a

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considerably lower level than was attained at their peak. This process was accompanied by marked changes in the vegetation, usually beginning with a change in grass species composition, followed by a decline in the perennial grass cover, and an increase in the biomass of annual grasses and woody vegetation. In the most extreme cases, woody vegetation in the form of scrub or thicket now dominates the final state, virtually excluding grasses.

Even if all the large herbivores are then removed the vegetation generally remains in its new state, at least for 20 yr, and does not revert to its original state. This general story has been described for many areas in the Sahel zone of Africa (Wickens & Whyte 1979), southern and eastern Africa (Barnes 1979), the south-western U.S.A. (Buffington & Herbel 1965; Clark-Martin 1975), the drier parts of India (Singh & Joshi 1979) and Australia (Wilson & Graetz 1979). In most cases the collapse is triggered by drought, and there is generally increased soil erosion and reduced infiltration of water into the soil. Fire is not an important factor and seems not to contribute to the change (in contrast with the wetter savannas).

Our objectives are to examine the dynamics of these systems and to understand how stable they are likely to be, and how they will behave under different forms of management. We begin with a general case, based on southern African experience, and use this to show how different situations can arise from inherent differences in the environment or structure of the system, or from differences in management.

DESCRIPTION OF THE SYSTEM AND NECESSARY ASSUMPTIONS

The many kinds of woody vegetation can be broadly grouped into the microphyllous, xerophytic *Acacia* forms and deciduous, longer-lived broadleaved forms (perhaps best typified by the family Combretaceae). The major components of the herbaceous layer are forbs, annual grasses and perennial grasses. These details can be simplified for our purposes, however, and the vegetation regarded as a mixture of woody vegetation and of perennial grasses, maintained in a stable equilibrium by the fact that they tap different sources of water in the soil (Walter 1971). Grasses are more efficient than trees in extracting water from the upper layers of the soil (topsoil), but below the grass root zone (in what is here called the subsoil) the woody vegetation has nearly exclusive use of whatever water gets through. Walker & Noy-Meir (1981) have explored this hypothesis further and have shown that in some conditions a single, stable equilibrium of woody vegetation and grasses exists. These conditions are that the proportion of a tree's water requirements obtained from the subsoil is sufficiently high, and that rainfall is enough for some water to infiltrate to the subsoil, but not so much that woodland can develop.

Because semi-arid savanna is a water-limited system, any reduction in the rate of water infiltration into the soil is critical. On medium to heavy-textured soils, infiltration decreases as the surface pores become sealed ('capping') and soil erodes, and both of these processes increase in rate as grass-cover and litter-cover decline. Kelly & Walker (1976) have demonstrated that the rate and amount of infiltration into a loamy savanna soil is about ten times greater under a grass–litter cover than it is through a bare soil surface. During heavy rainfall, the difference is crucial and leads to run-off from, and erosion of, bare soils. Similar reports have been made for the semi-arid ranges in the south western U.S.A. (e.g. Glendenning 1952; Buffington & Herbel 1965). The biomass of grass is therefore a critical factor in determining the rate and amount of infiltration.

On the other hand, woody plants can influence the water content of the subsoil. The canopy intercepts rain and funnels it down the stem and into the soil at the tree base. Pressland (1973), working in an Australian savanna, has recorded a six-fold increase in the amount of water percolating into the soil below trees as compared to open areas, and Reynolds (1966) has noted a similar phenomenon in a British woodland. Further means by which water penetrates preferentially to the subsoil are the quick-flow channels or tongues of preferred flow associated with wetting front instability, (P. de Vries, personal communication). As a result of these channels, water moves rapidly into the subsoil before the topsoil is at field capacity. The net result is that, although less water will infiltrate the topsoil if grass cover declines, there is, rather surprisingly, a relatively smaller reduction in the amount of water reaching the subsoil. If the reduction in infiltration is not too drastic, then, as the amount of grass declines, less water will be taken up from the topsoil by plants, and so more will penetrate to the subsoil.

Rainfall is here assumed to be generally constant but interrupted by periodic droughts, which result in the death of many plants, especially those grasses and woody plants in the process of establishment.

Cattle and sheep are the major herbivores and eat negligible amounts of woody vegetation. In Africa, at least, cattle do not inhibit woody plant regeneration (Taylor & Walker 1978) and, if anything, increase the rate of dissemination of seeds and pods. Under high stocking levels the common pattern of range deterioration is: reduced biomass of grass, leading to reduced infiltration, which further reduces the rate of growth of vegetation, particularly of grasses. The decrease in the biomass of grass is accompanied by an increase in that of woody vegetation.

This shrub-dominated state is remarkably stable and, if the cattle are removed, does not revert at once to open grassland. Over a long period of time (how long is not known) the system would probably slowly change, with a gradual improvement in the soil surface conditions, which would re-establish the predominance of topsoil water and allow an increase in the biomass of grasses.

PROCEDURE

Our analysis consisted of two phases. First, we identified the important variables, and used graphs to understand the factors which govern their dynamics. Secondly, we expressed the behaviour of the system algebraically, and manipulated it mathematically to allow a better understanding of the quantitative response of the system to changes in the values of the variables and parameters.

The mathematical procedure was similar to that described by Ludwig, Jones & Holling (1978). The state variables were divided into 'fast' and 'slow' categories, according to the time-scale over which they change. At first, the values of the slow variables were fixed, and the fast ones allowed to reach steady state values. Thus the potential equilibria of the fast variables could be expressed in terms of the slow ones. This procedure greatly simplified the subsequent analysis of the dynamics of the combined system.

SELECTION OF STATE VARIABLES

In southern Africa there are five essential variables: topsoil and subsoil water content (cf. Walker & Noy-Meir 1981), the biomass of grass, of woody vegetation, and of herbivores.

It would be possible to subdivide the vegetation variables since it is well established that (at least) there are differences in growth and survival rates of perennial and annual grasses (Kelly & Walker 1976), in the palatability to, and consumption by, herbivores of various grasses (Gammon & Roberts 1978; Kennan 1969) and in the susceptibility to drought and competition of establishing and established plants (Glendenning 1952). There is no clear evidence as to how these differences affect the final outcome of the woody vegetation–grass combination, however, and we therefore proceed with just the two broad categories and consider the differences as specific effects at a later stage.

A simple, but still effective representation, does not need all the five variables explicitly. For example, the two most rapidly changing variables, topsoil and subsoil water, are totally dependent on other variables: they depend on infiltration rate, on the biomass of grass and of woody vegetation, and, to a much lesser extent, on leaching and evaporation losses. The effects of changes in the amounts of topsoil and subsoil water can, therefore, be expressed by changes in the biomass of grasses and of woody vegetation, and of infiltration rate.

Infiltration rate itself depends largely on the amount of grass cover at any one site, but it is convenient to retain infiltration rate in the analysis. There is some (empirical) evidence that under conditions of low grass cover, a moderate amount of animal hoof action breaks up soil surface crusts and can increase infiltration. This effect is difficult to quantify and is not generally agreed upon. In any case it is of minor significance when compared to the effect of grass cover, so we omit it in this analysis.

Finally, in a natural ecosystem the population of herbivores fluctuates in a complex way in response to changes in the other system variables. Under ranching conditions, however, the herbivore population can be considered as a constant. Stocking rates are set and maintained by the manager and, usually, are not altered until drastic changes (such as death of animals) have occurred. The dynamics of the herbivore population can therefore be omitted, and the analysis reduces to an examination of the remaining variables under various fixed values of herbivore biomass.

Hence the effects of all five essential variables can initially be reduced to the interactions between only two of them, i.e. the biomass of grass (G) and of woody vegetation (W), and their effects on infiltration rate (I). These variables will be referred to henceforward by their symbols.

GRAPHICAL ANALYSIS

Changes in the relationships between G and W are linked to the soil water variables by changes in I (assuming an average annual rainfall) and it is therefore necessary to establish the form of the relationship between G and I. In the absence of any grass there will still be some infiltration (i_0). This minimum is likely to be about 10% of the maximum (Kelly & Walker 1976). The rate of infiltration will initially increase rapidly as G increases and then approach the maximum asymptotically with increasing G, as depicted in Fig. 1. For convenience, the rate is expressed as a proportion of the maximum rate, and is thus dimensionless. It is referred to as a 'rate' for convenience. The value of i_0 and rate of increase will vary from site to site, largely as a function of soil texture. On loose, sandy soils both the value of i_0 and the rate of increase in I will be high, and both will be low on clay soils. Unless otherwise specified, the effects of I in the following graphs assume a medium or heavy textured (clay) soil.

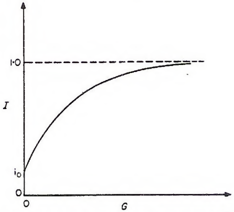

FIG. 1. Hypothesized relationship in semi-arid savanna between rate of water infiltration into the soil (I), expressed as a proportion of the maximum rate, and the biomass of grass (G).

Grass dynamics

Grass biomass (G) changes more quickly than does that of woody vegetation (W) and it is consequently analysed first. In the absence of woody vegetation and herbivores the dynamics of G is controlled by available soil water. For the moment we ignore the effects of I (I_0 in Fig. 2). When G is small little water is used and the annual rate of increase in grass from one year (t) to the next (t + 1) is large. As G increases, so does water uptake and the annual increase in grass becomes smaller until it finally becomes zero and, if for some reason G exceeds the biomass which can be sustained by the available water, negative. It is convenient to call this the recruitment curve for G. The point E, where $R = G_{t+1}/G_t = 1$, represents a stable equilibrium if all other variables are fixed.

Inclusion of the effects of infiltration leads to a depression in the recruitment curve at low values of G, as shown by I_1 and I_2 in Fig. 2. At higher values of G infiltration is reduced very little as G becomes smaller, because the litter cover remains high. Only when the biomass of G is small is the effect significant. The reduced infiltration leads then to less

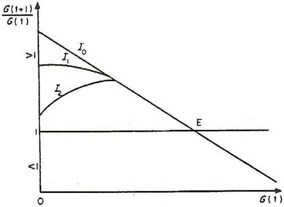

FIG. 2. Hypothesized recruitment curve (see text) in semi-arid savanna for grass biomass (G). The point E represents a stable equilibrium if all other variables are fixed. I_0 is the relationship when I has no effect on recruitment. I_1 and I_2 represent cases in which reduced infiltration at low values of G affect recruitment.

growth. Whether recruitment continues to rise as G becomes smaller (I_1 in Fig. 2), or curves downwards (I_2) depends on whether or not the reduction in the amount of water infiltrating is more or less than the reduction in water uptake by the reduced biomass of grass. Our own observations of recovery rates on areas where G has been kept very small through overgrazing suggest that both conditions are possible and that I_2 is not uncommon. In other words, the proportional recruitment of grass may be greater at intermediate values of grass biomass than at low (or high) values. Because some infiltration will always occur (i_0, Fig. 1), the curve will never be depressed below 1 at low values of G, and there remains the single equilibrium value of G, at E.

Woody vegetation competes with grass for water in the top-soil, and there is ample evidence from semi-arid regions all over the world (e.g. Barnes 1979; Walker, Moore & Robertson 1971; Medellin-Leal & Gomez-Gonzalez 1979) to suggest that, ignoring infiltration, the effect of increasing W on the recruitment curve of G is that shown in Fig. 3. With small to medium values of W the effect is greater at high values of G than at small ones, because when there is little grass and few trees, water uptake is less.

Combining the effects of infiltration and woody vegetation results in the recruitment curves shown in Fig. 4. These are qualitatively different from the individual effects because

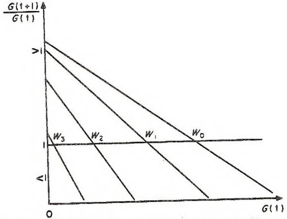

FIG. 3. Hypothesized effect on the recruitment curve for G, in semi-arid savanna, of increasing amounts of woody vegetation from none (W_0) to woodland or thicket (W_3).

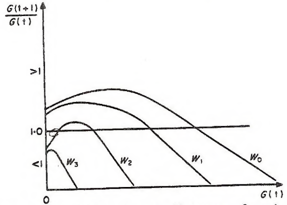

FIG. 4. Hypothesized combined effects, in semi-arid savanna, of woody vegetation and of reduced infiltration at low G (I_2 of Fig. 2) on the recruitment curve for G.

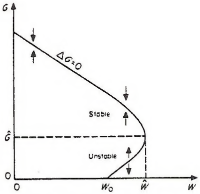

FIG. 5. Equilibrium conditions for grass biomass ($\Delta G = 0$) in relation to grass biomass (G) and woody biomass (W). The grass zero-isocline is the locus of points for which G is in equilibrium ($R = G_{t+1}/G_t = 1{\cdot}0$; $\Delta G = 0$) at the given value of W. Arrows show the direction of movement for small departures from the isocline. There are two equilibria for W between W_0 and $\hat{W}$; the upper is stable and the lower unstable.

we assume that at some large values of W there are now two intersections of the recruitment curve with the $G_{(t+1)}/G_t = 1$ line, giving the usual stable equilibrium point at high values of G, and also an unstable one at low values of G. This lower equilibrium is unstable because at even smaller values of G_t, the recruitment rate R ($= G_{t+1}/G_t$) is less than 1 and the grass biomass declines. At G_t values just greater than the equilibrium, however, $R > 1$ and G increases. The locus of these equilibria as a function of W can be shown on a graph of G *v.* W (Peterman, Clark & Holling 1979), as in Fig. 5. We call the locus of equilibrium points the grass zero-isocline. It is central in our argument.

Herbivores affect grass, directly, by eating it and by standing on it. Trampling becomes significant only at very high levels of stocking, and is trivial in comparison to the effects of defoliation. It is therefore not considered further. Light grazing has a stimulating effect on grass growth (McNaughton 1979), and leads to a higher grass biomass than occurs when the grass sward is ungrazed for any length of time, as the sward then becomes moribund and the proportion of old, dead grass in the standing crop increases. Kelly & Walker (1976) found that under complete protection from grazing for more than 5 yr the above-ground seasonal grass production in two successive years was about 66% and 80% of that under very light grazing. As grazing becomes heavier, however, grass production decreases until under very heavy grazing the grass plants are killed. These effects of increasing herbivore biomass (H) on the grass recruitment curve are summarized in Fig. 6. The stimulating effect of H_1 does not occur at low values of G because, although light grazing results in only light defoliation if there is a lot of grass (high values of G), it causes proportionately increasingly severe defoliation at lower values of G, and, also, because the build-up of large amounts of dead grass occurs only at high values of G. At low values of G, dead grass falls to the ground as litter, and has a beneficial effect.

It may at first seem strange to conclude, as we do in Fig. 6, that larger amounts of grass are apparently less able to sustain high levels of stocking than are the intermediate amounts. However, the curves represent net grass recruitment, which is approximately the product of R for H_0 with G, less the amount eaten (which is constant until it approaches G). This product is maximal at some intermediate value of G. The depression of the curve to below the $R = 1$ line at large values of H, once again implies the existence of an unstable

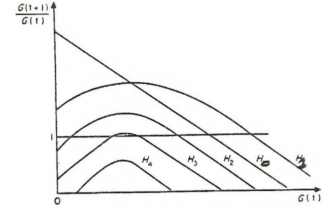

FIG. 6. Hypothesized effects in semi-arid savanna of increasing herbivore biomass from none (H_0) to heavily overstocked (H_4), on the grass recruitment curve. Note the order of H_0 and H_1 at high values of G.

equilibrium at small values of G, and a stable one at larger values. Theoretical and empirical evidence for this unstable equilibrium at small values of G are presented in Noy-Meir's (1975) lucid account of grazing systems. The zero-isocline of G on a graph of G *v.* H is shown in Fig. 7.

Finally, the combined effects of I, W and H on the equilibrium positions (zero-isocline) of G are shown in Fig. 8 on the graph of G *v.* W for various values of H. The effects of infiltration (I) are implicit in these curves.

Woody vegetation dynamics

Woody vegetation dynamics are far simpler than those of grass because herbivores do not affect them significantly, and because the depressive effect of reduced infiltration when there is little grass is relatively small. The woody vegetation has exclusive access to subsoil water, so high values of G cannot depress the recruitment curve below 1 (Fig. 9), and the resulting zero-isocline for W appears as in Fig. 10, with the dotted line indicating the effects of reduced infiltration at low values of G. Woody vegetation cannot, therefore, be eliminated by competition from grasses (though the reverse is possible). This conclusion is based on the more detailed analysis by Walker & Noy-Meir (1981).

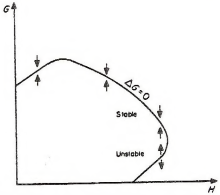

FIG. 7. The grass zero-isocline in relation to G and H, resulting from the effects in Fig. 6. See text and Fig. 5 for further explanation.

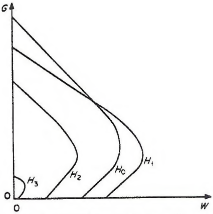

FIG. 8. The grass zero-isocline (zero recruitment; $R = G_{t+1}/G_t = 1{\cdot}0$; $\Delta G = 0$) in relation to G, W and H. The effects of infiltration (I) are implicit in the shapes of the curves, which summarize those of Figs 5 and 7.

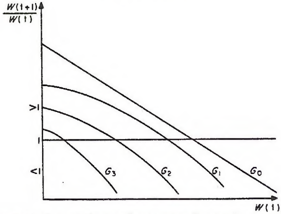

FIG. 9. Hypothesized effect on the recruitment curve for woody vegetation (W), in semi-arid savanna, of different biomass of grass from woodland (G_0) to nearly open grassland (G_3).

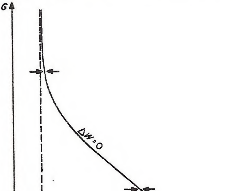

FIG. 10. Equilibrium conditions (zero-isocline) for woody biomass ($\Delta W = 0$) in relation to grass (G) and woody (W) biomass. The recurved dotted line indicates the effects of reduced infiltration at low values of G, and the dashed line (W_∞) is the asymptote (see text). This graph is the counterpart of that for grass in Fig. 5.

Combined dynamics

The dynamics of the system as a whole can now be summarized as follows. In average conditions the bulk of the rainfall enters the topsoil and is preferentially taken up by grass roots. Some, however, is taken up by tree roots and when there is heavy or continuous rain, or both, some penetrates to the subsoil, where it too is taken up by tree roots. A single reduction in the amount of grass to some very low value does not cause an immediate change in the equilibrium conditions, because of the slower response of infiltration characteristics and (even slower) response of the amount of woody vegetation. If the grass biomass is maintained at a low value for a sufficiently long time (e.g. by several years of sustained intense grazing) then the soil surface changes and infiltration rate declines with the result that less water enters the soil but proportionately more of what does enter may penetrate to the subsoil. The combined result is that woody vegetation may have more water available to it, so the biomass of woody vegetation increases. These two factors—reduced infiltration and greater biomass of woody vegetation—combine to prevent the re-establishment of grasses even if the grazing pressure is reduced. Only if one or both of these factors are altered to allow the grass to develop to above the critical, unstable equilibrium ($\hat{G}$ in Fig. 5), will the system revert to its original structure. It may require more than a single reduction in above-ground woody vegetation to achieve this, as the root systems of savanna trees are remarkably extensive and persistent. The competitive effect of the woody plants must be removed for long enough to allow the grass root system to develop to the point where it can once again take up more water than the tree roots, and thus allow the grass cover to increase and, eventually, infiltration (to the topsoil) to increase.

This graphical analysis has proved useful in providing a conceptual understanding of the dynamics, but further progress is not possible without a more detailed quantitative understanding of the response of the system to changes in particular parameters. We proceed therefore, to a more detailed analysis of these ideas. The parameters introduced here are summarized in Table 1 (p. 490).

QUANTITATIVE ANALYSIS

The interpretation of equations and their parameters is greatly simplified if a consistent system of units is adopted. In this analysis, the use of [ ] indicates the units, and hence the dimensions, of the variable or parameter they enclose. This convention is superior, for our purposes, to the use of simple physical dimensions of mass, length and time because although the biomass of grasses and herbivores (for example) have the same physical dimensions it is not usually valid to add them. In places where the dimensions are obvious we omit specific definitions.

Grass dynamics

Change in the biomass of grass is determined by five factors: the amount of water in the soil, the proportion of this amount which is taken up by grass, the efficiency of conversion of the water that has been taken up into grass biomass, the loss of biomass by respiration and death, and consumption by herbivores.

Amount of soil water

As described previously, if we assume an average annual rainfall the amount of soil water is a function of the rate of infiltration, I, which we define in relative terms as the amount of water entering the soil expressed as a proportion of the amount which enters when G is at a maximum (Fig. 1). Therefore, I is dimensionless and has no units.

The form of the relationship between I and G, described by Fig. 1, will be developed in several steps. The saturation effect, modelled by a hyperbolic relationship, may be expressed in Michaelis-Menten form as

$$I = \frac{G}{G + \mathrm{d}_1}$$

where d_1 is the value of G where I reaches half its maximum, i.e. $I = 0{\cdot}5$. However, we require a non-zero infiltration fraction when $G = 0$, so we displace the origin of the G axis by d_2.

$$I = \frac{G + \mathrm{d}_2}{G + \mathrm{d}_2 + \mathrm{d}_1}.$$

When $G = 0, I = \mathrm{i}_0$ is given by

$$\mathrm{i}_0 = \frac{\mathrm{d}_2}{\mathrm{d}_1 + \mathrm{d}_2} = \frac{\mathrm{d}_2}{\mathrm{c}_1}.$$

Then

$$I = \frac{G + \mathrm{c}_1.\mathrm{i}_0}{G + \mathrm{c}_1}. \qquad (1)$$

Water uptake

We define a parameter U_G, which is the relative utilization of topsoil water per unit of grass biomass, such that $U_G\ G$ gives the utilization of water by grass, expressed as a proportion of the total amount of water available (Walker & Noy-Meir 1981). It is defined by

$$U_G = \frac{\theta_G}{\theta_G.G + \theta_W.W + \mathrm{e}}; \quad [U_G] = 1/[G]. \qquad (2)$$

where θ_G and θ_W are the rate of water uptake (as a depth of water per unit time) per unit biomass of grass and woody vegetation respectively, and e is the loss of water (as depth per unit time) by evaporation. If l is the rainfall in a given time, T, then $[\theta_G] = [l]/[G][\mathrm{T}]$; $[\theta_W] = [l]/[W][\mathrm{T}]$ and $[\mathrm{e}] = [l]/[\mathrm{T}]$. The evaporation loss is generally insignificant and has little effect on the dynamics of the system, but is included for the sake of completeness. U_G is therefore a term which reflects the competitive effect of woody vegetation in reducing the amount of water taken up by grasses.

Conversion efficiency of water into grass biomass

This can be considered as the growth rate (productivity) of grass, denoted by r_G; $[\mathrm{r}_G] = [\mathrm{G}]/[\mathrm{T}]$. It is a measure of the increase in the biomass of grass during a given time which results from the total amount of water taken up.

Losses by respiration and death

Let L_G denote the proportional rate of loss of grass biomass; $[\mathrm{L}_G] = 1/[\mathrm{T}]$. Then $G\ \mathrm{L}_G$ is a measure of the grass biomass lost per unit time.

Consumption by herbivores

The stimulating effect on grass growth, described by Fig. 7, is not included here for two reasons. First, it affects only the upper parts of the grass isocline (when the biomass of grasses is large), and therefore has no effect on the qualitative behaviour of the system, which is determined by the change from stable to unstable equilibrium when grass biomass is small. Secondly, as already described, it is difficult to quantify the stimulating effect in terms of individual plant effects (as opposed to the accumulated effects on the sward as a whole).

Losses due to grazing must incorporate the two features shown in Fig. 11, where the relation between total consumption, C, at a fixed level of grazing, and the grass biomass, G, is shown. The consumption asymptotically approaches a satiation level as G increases (cf. Morley 1966; Noy-Meir 1975). Below some minimum value of G no grazing occurs, either because it is impossible (the animals cannot get at the grass) or because food quality or some other feature of the grass–herbivore interaction renders the grass unacceptable to the herbivores. When considered over a short time (a few seasons), recruitment of grass is a function of total biomass, above and below ground. Over 50% of the biomass of many savanna grasses may be below ground (e.g. Rushworth 1975; Kelly & Walker 1976). Even if all of the above-ground biomass is removed, re-growth will occur the following season. Defoliation at this intensity, if continued, will kill the plants, but in the short term the stolons and rhizomes supply a refuge. A further mechanism that allows some grass to survive above ground is the development of a creeping growth habit. It is a commonly observed phenomenon that grasses with this ability (e.g. *Cynodon* spp.*) tend to take over from erect bunch grasses (e.g. species of *Brachiaria*, *Setaria* and *Themeda*) under heavy grazing, and McNaughton (1980), working in the Serengeti, describes how some grasses change their growth habit under different grazing pressures.

There are a variety of reasons why herbivores will not eat certain kinds or quantities of grasses. Wilson & Graetz (1979) described an Australian grassland where the nutritive value of all but a small percentage of the plant parts is too low to be of any use to domestic livestock. Similar types (e.g. *Eragrostis pallens*) occur in southern Africa. Some grasses are unpalatable owing to taste, e.g. species of the genera *Cymbopogon*, *Bothriochloa*, *Trachypogon*, *Elyonurus* and *Urelytrum*, and others because they are too tough and fibrous, e.g. *Eleusine indica*, *Aristida junciformis*, some *Sporobolus* spp., and so on.

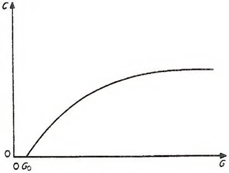

FIG. 11. Hypothesized relation between total consumption (C) of grass on semi-arid savanna at a fixed level of herbivore biomass, and the biomass of grass (G). Below G_0 no grazing is possible.

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* Nomenclature follows Simon (1971).

The combined effect of these different mechanisms is the grazing cut-off, represented by G_0 in Figs 11 and 12. The value of G_0 can vary considerably.

We may incorporate the saturation and cut-off effects by following the procedure which led to Eqn (1). The rate of consumption of grass, Q, can be described by

$$Q = \max\left(\frac{c_2 H(G - G_0)}{G + c_3}, 0\right) \qquad (3)$$

where c_2 = rate of consumption of grass biomass per unit of herbivore biomass; $[c_2] = [G]/([H][T])$; and d_3 = the value of G at which the consumption rate is half maximum, and $c_3 = d_3 - G_0$.

Now we have terms which correspond to each of the factors which affects the change in the biomass of grass. The combined equation is

$$\frac{dG}{dt} = r_G I U_G G - L_G G - HQG. \qquad (4)$$

Here we have set

$$U_G = \frac{1}{G + \alpha W + \beta} \qquad (5)$$

where $\alpha = \theta_w/\theta_G$; $\beta = e/\theta_G$; and

$$Q = \max\left(\frac{c_2(1 - G_0/G)}{G + c_3}, 0\right).$$

The zero isocline for G (that is the equilibrium line shown in Fig. 5) is the curve where $dG/dt = 0$. From Eqn (4), we see that this curve has two branches: $G = 0$ (a trivial result) and

$$\frac{r_G I}{G + \alpha W + \beta} = L_G + QH$$

After substitution of Eqn (1), this relation may be solved for W:

$$W = \frac{1}{\alpha}\left\{-\beta - G + \frac{r_G}{L_G + QH}\left[1 - \frac{c_1(1 - i_0)}{G + c_1}\right]\right\}. \qquad (6)$$

The intercept of this isocline with the W axis is obtained by setting $G = 0$ in Eqn (6) and is

$$W_0 = \frac{1}{\alpha}\left(\frac{r_G . i_0}{L_G} - \beta\right). \qquad (7)$$

The value of W_0 is independent of H (provided $G_0 > 0$) because of the grazing cut-off. The slope of the isocline may be obtained by differentiating Eqn (6). If G is large, it can be shown that this slope is negative. Where $G = 0$, we have

$$\left.\frac{dW}{dG}\right|_{G=0} = \frac{1}{\alpha}\left[-1 + \frac{r_G(1 - i_0)}{L_G c_1}\right]. \qquad (8)$$

This expression will generally be positive. Thus Eqn (6) when differentiated will have a root: the corresponding point ($\hat{W}$, $\hat{G}$; Fig. 5) is a 'turning point' for the isocline. The unstable section at low values of G is due to reduced infiltration when the biomass of grass is small.

Now we consider the effect of the herbivore biomass upon the isocline. If $G > G_0$, then $Q > 0$. As H in Eqn (6) increases, the factor $r_G/(L_G + QH)$ decreases. The quantity in brackets which multiplies it is positive. Hence the isocline moves to the left as H increases. Finally, for very large values of H, the isocline will coincide with a segment where $G = G_0$. If $G \leqslant G_0$, the isocline does not depend on H. The net effect is shown in Fig. 12.

Woody vegetation dynamics

The equation for the change in woody vegetation will be developed in a similar way to that for grass, except that the woody vegetation has access to subsoil water, which is not available to the grass. The Michaelis–Menten form of the hyperbola is adequate: the extra term has the form $r_s W/(W + p)$. Here r_s = increase in biomass of woody vegetation, during a given time, for the subsoil water taken up, $[r_S] = [W]/[T]$; and p = biomass of woody vegetation which might have been formed in response to water lost by percolation beyond the roots in the subsoil (i.e. a measure of the inefficiency of subsoil water use; $[p] = [W]$.

There is one further modification. If G decreases, the total amount of water entering the soil decreases but, as there is very little grass to take it up, there may be more water passing through to the subsoil (depending on soil type and the value of i_0). This means that r_S is not constant, but is a function of G, in the opposite sense to I. We therefore set

$$S = r_s[1 - G/(K(G + d_4))]$$

where r_s = the increase in biomass of woody vegetation at $G = 0$, during a given time, for the subsoil water taken up; K determines the proportional reduction from r_s to the lower asymptotic value of $S = r_s(1 - 1/K)$ at high values of G; and d_4 = the half saturation value of G. Usually, K will be greater than or at least equal to 1, but if i_0 is very low, it could drop below 1.

By analogy with Eqn (5), we set

$$U_W = \frac{\theta_W}{W\theta_W + G\theta_G + e} = \frac{1}{W + \gamma G + \delta} \qquad (9)$$

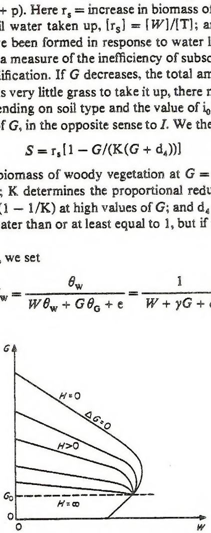

FIG. 12. Equilibrium conditions ($\Delta G = 0$) for grass biomass in relation to grass biomass (G) and woody biomass (W) at various grazing levels (herbivore biomass. H). The cut-off value G_0 is the biomass of grass below which stock do not eat the grass. See text and Fig. 5 for further explanation.

where $\gamma = \theta_G/\theta_W = 1/\alpha$ and $\delta = e/\theta_W = \beta/\alpha$. Dimensions are defined by $[U_W] = 1/[W]$; $[\gamma] = [W]/[G]$; and $[\delta] = [W]$. Thus the dynamic equation for W has the form

$$\frac{dW}{dt} = r_W\, I\, U_W\, W + SW/(W + p) - L_W\, W \tag{10}$$

where r_W and L_W (analogous to r_G and L_G) represent the growth rate due to topsoil water uptake, and the proportional rate of loss (by respiration and death), respectively. A consumption term is omitted from Eqn (10), because virtually no woody vegetation is eaten by stock.

The zero isocline for W (the equilibrium line shown in Fig. 10) is obtained by setting $dW/dt = 0$. The two branches are given by $W = 0$, and

$$r_W I U_W + \frac{S}{W + p} = L_W. \tag{11}$$

The intercept W_1 of this isocline with the W axis is obtained by setting $G = 0$ in Eqn (11).

If G is large, U_W is small and the first term in Eqn (11) is negligible. Thus the isocline has a vertical asymptote: $W = W_\infty$. From Eqn (11) it follows that

$$W_\infty = \frac{S}{L_W} - p. \tag{12}$$

Now we turn to intermediate values of G. As a first step, the effect of G upon infiltration may be ignored; thus we set $I = 1$ in Eqn (11). The equation of the isocline then takes the approximate form

$$\frac{r_W}{W + \gamma G + \delta} + \frac{S}{W + p} = L_W. \tag{13}$$

If G increases, the first term in Eqn (13) decreases. The balance can only be made up by a decrease in W. Therefore the biomass of woody vegetation decreases as that of grass increases. This relationship may not hold when there is very little grass, because of the effect of grass upon infiltration. The effect upon the W isocline will depend upon whether the benefit to woody vegetation of a reduced uptake of water by grass is offset by the reduced infiltration. The general form of the isocline is shown in Fig. 10.

Combined dynamics

When the zero isoclines (equilibrium lines) for G and W are combined, the result can be as shown in Fig. 13. The details may change as parameter values are changed. There may be two stable equilibria in the absence of herbivores. The equilibrium point with large biomass of grass and small biomass of woody vegetation may be regarded as the usual condition. The two stable equilibria are separated by a saddle point, which is an unstable equilibrium. The whole area of the grass biomass–woody vegetation biomass graph may be divided into two parts, each containing a stable point. From anywhere within one area the vegetation will tend to move toward the stable point. The line defining these areas is the separatrix (Fig. 13), and its position is determined by the relative speeds with which G and W change, not merely by the the positions of the isoclines.

Varying the parameters in the model, in various combinations, leads to two main changes in the relative positions of the isoclines. First, the W zero-isocline moves to the right if S (the rate of growth of W due to subsoil water) increases or if L_W (metabolic loss

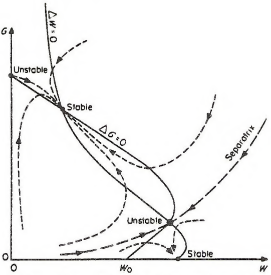

FIG. 13. Probable relative positions of the G and W zero-isoclines (locus of points of equilibrium where, for $X = G$ or W, $X_{t+1}/X_t = 1{\cdot}0$; $\Delta X = 0$) in relation to biomass of grass and of woody vegetation. There are two stable and two unstable equilibria. The stable equilibria are separated by an unstable equilibrium, or saddle point. The dashed lines show the directions of movement of a system not at equilibrium. The interrupted line (separatrix) defines areas from within which a system would move to one or other of the stable positions.

rate of W) or p (percolation loss) decrease (Fig. 14). Eventually the two intersections of the zero-isoclines are lost, and woody vegetation dominates. In the reverse situation, if S decreases or if L_w or p increase, the W zero-isocline moves to the left, with two possible

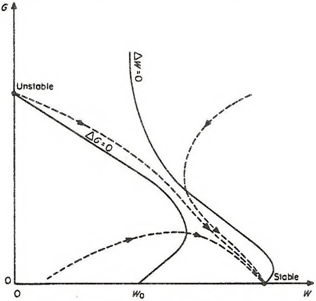

FIG. 14. Effect on the woody vegetation zero-isocline ($\Delta W = 0$) of increasing S (the rate of growth in response to subsoil water) or of decreasing L_w (respiratory loss) or p (percolation loss). The grass zero-isocline is in the same position as it is in Fig. 13, and does not intersect the $\Delta W = 0$ line. All mixtures move toward domination by woody vegetation.

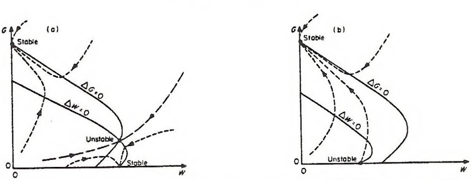

FIG. 15. As in Fig. 14 but decreasing S or increasing L_W or p. The $\Delta W = 0$ line moves to the left. In (a) there are two stable points. In (b), where the zero-isocline has moved even further left, grassland alone is stable.

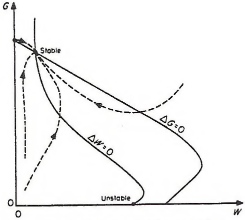

FIG. 16. Effect on the grass zero-isocline ($\Delta G = 0$) of increasing i_0, r_G or G_0, or of decreasing α, L_G or H (see Table 1 for definition of symbols). The woody vegetation zero-isocline is in the same position as it is in Fig. 13. All mixtures move towards a single stable mixture.

outcomes. In Fig. 15(a) the upper intersection is lost and the result is that either grass or woods vegetation dominate, depending on which side of the separatrix the system starts from. In Fig. 15(b) both intersections are lost and grass comes to dominate. Secondly, the G zero-isocline may be moved: to the right if i_0 or r_G or G_0 increases, or if α or L_G or H decrease. The lower intersection eventually disappears, leading to a single stable equilibrium and co-existence of grass and woody vegetation (Fig. 16). If the parameters change in the opposite direction, the G zero-isocline moves to the left until eventually the same situation occurs as in Fig. 14, and grass is eliminated.

Example from an 'average' savanna

As a final step in our analysis it was necessary to establish whether the basic situation as depicted in Fig. 13 can, or actually does, occur. To do this we need to quantify the variables and parameters of the model, and to test the effects of changing them. A complete set of values does not exist for any one site, but an 'average' semi-arid savanna was synthesized from various sources (Kelly 1973; Rutherford 1979; Huntley & Morris 1978; Walker & Noy-Meir 1981). Where no data were available, such as for the partition of total

TABLE 1. The parameters used in the model of grass and woody vegetation dynamics. The values in parentheses are those used for the standard run of the model, shown in Fig. 17.

Parameters for grass:	
r_G	rate of growth due to topsoil water (4000 kg ha^{-1} yr^{-1})
c_2	rate of consumption of grass by herbivores (3·15 kg kg^{-1} yr^{-1}; at $H = 100$ kg ha^{-1})
G_0	the grazing threshold (500 kg ha^{-1})
d_3	half-saturation level for grazing (600 kg ha^{-1})
i_0	minimum infiltration at low values of G (0·1)
c_1	the rate at which infiltration increases with G $c_1 = d_1 + d_2$; $d_1 = 500$ kg ha^{-1}; d_2 is derived from other parameters, see p. 483.
α	the quotient of the efficiency of uptake of water from topsoil by woody vegetation to that by grasses ($=\theta_W/\theta_G$; $\theta_G = 0{\cdot}21$ mm kg^{-1} ha^{-1} yr^{-1}; $\theta_W = 0{\cdot}122$ mm kg^{-1} ha^{-1} yr^{-1})
L_G	the proportional rate of loss of grass by respiration and death (1·0 yr^{-1})
Parameters for woody vegetation:	
r_W	rate of growth due to topsoil water (3000 kg ha^{-1} yr^{-1})
r_s	rate of increase of biomass of woody vegetation due to subsoil water taken up at $G = 0$ (4000 kg ha^{-1} yr^{-1})
d_4	half-saturation value of G for the decrease in S with increasing G (500 kg ha^{-1})
K	proportional reduction from r_s to lower asymptote of S at high values of G (2·0)
p	biomass of woody vegetation which might have been formed by water lost through the subsoil by percolation (inefficiency of sub-soil water use) (0·1 kg ha^{-1})
L_W	the proportional rate of loss of woody vegetation by respiration and death (1·0 yr^{-1})

woody vegetation growth into that due to topsoil-water and that due to subsoil-water, (r_W and S), the estimated minimum and maximum values were tested. In the absence of better information, losses from respiration and death (L_G and L_W) were made equal, and subsoil water loss (p) and evaporation loss (e) were kept at very low values. The standard set of values used for what was considered to be an average semi-arid savanna with soils prone to capping, under light grazing, are shown in Table 1. The position of the separatrix was obtained by plotting the trajectories of G and W, starting at various positions along the W axis and increasing G until the direction of the trajectory changed. The results of the standard run are given in Fig. 17.

With the parameter values given in Table 1, the multiple equilibrium situation does arise, and changes in the parameters lead to the expected relative changes in the position of the

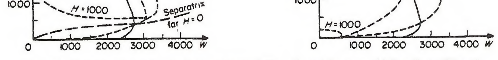

FIG. 17. Zero-isoclines for woody vegetation ($\Delta W = 0$) and for grass ($\Delta G = 0$) at different herbivore biomass (H) using parameter values given in Table 1. In (a) with grazing threshold 500 kg ha^{-1}, the upper equilibrium exists for all values of H. In (b) with grazing threshold 10 kg ha^{-1}, grass is eliminated when H is slightly less than 100 kg ha^{-1}.

grass zero-isocline. A number of interesting consequences emerge from the results obtained by varying the parameter values, as described in the next section. At this stage, one important result is worth noting. With a value of i_0 (infiltration minimum) greater than 0·5 and with a low value of K (proportional increase in subsoil water as grass biomass decreases) there are only two equilibria: the single stable joint equilibrium (with grass and woody vegetation) and woody vegetation alone. Because i_0 has such a powerful effect, an unstable threshold does not occur on sandy soils (for which i_0 is large) and the system will always be able to return to a joint equilibrium (provided grass is not totally eliminated). Furthermore, if $K \leqslant 0$ then even at very low values of i_0 the unstable joint equilibrium either does not exist or it occurs very close to the W-axis, virtually at $G = 0$. This highlights the importance of changes in the absolute amount of water passing through to the subsoil as the biomass of grass decreases. There are, as yet, no empirical tests of this prediction, but two studies have been initiated in South African savanna to obtain estimates of K and d_4.

EFFECTS OF GRAZING AND MANAGEMENT

We return now to the theme of the introduction, using the stability analysis to suggest explanations for the observed impact of different patterns of grazing on semi-arid savannas. We describe four different patterns emerging from inferred differences in the form and relative positions of the isoclines. These four examples are then used to define the responses of the grass–wood vegetation systems to disturbance.

Grazing prior to 1800

Prior to the main impact of European settlement, the savannas of southern and eastern Africa were grazed by many species of native ungulate and by the cattle of semi-nomadic herdsmen. Human population density was low, especially in the drier regions where, apart from the permanently watered areas along rivers, grazing by cattle was irregular and opportunistic, depending on the rainfall. Because of the migratory behaviour of the native ungulates and the movements of the herdsmen any one area was grazed fairly lightly for most of the time, but periodically it was grazed heavily, followed by a period of recovery. A number of perennial grasses, including many early successional species (hereafter referred to as 'resistant' grasses), can withstand intense grazing because a significant proportion of their biomass is underground. In addition, some develop a recumbent habit when grazed and others are unpalatable and of low value as food. At the other end of the spectrum are the palatable, leafy perennials, regarded as desirable by range managers. These grasses, while more productive, are more 'sensitive' because they lack the underground refuge or recumbent habit and are the first to be grazed. Hence the particular balance achieved between the two types is the result of the shifting dynamics of competition between them. During periods of intense grazing, resistant grasses are favoured; during periods of low or moderate grazing, the sensitive grasses are favoured.

The resulting zero-isoclines for pre-1900 are suggested in Fig. 18(a), together with a typical trajectory. Two equilibrium conditions are possible—one allowing coexistence of grasses and woody vegetation and the other in which woody vegetation predominates. On the one hand, overall grass productivity is fairly high because the productive sensitive grasses are maintained in the system. On the other, persistence at the upper equilibrium, with grasses dominant, is encouraged because of the maintenance of resistant grasses (those with a high G_0). In these conditions, the system is insensitive to even unusually large

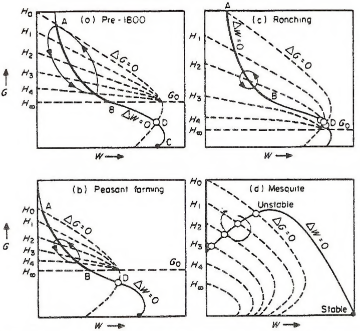

FIG. 18. Zero-isoclines, as in Fig. 17, for different herbivore biomass (H) in four situations. Large filled circles on the W axis and thick lines represent stable equilibria with grass and woody vegetation coexisting. Unfilled circles indicate unstable equilibria. Arrowed ellipses represent the normal variability in G and W under the different forms of land-use: (a) southern Africa, pre-1800: (b) southern Africa, settled peasant farmers, stock grazing: (c) southern Africa, ranching, fixed moderate level of stocking: (d) south-western U.S.A., mesquite grassland.

changes of the variables. In this simplified caricature, herbivore density could even rise to infinity, and the available grass biomass could go to zero, without the system moving to the lower equilibrium. In addition, the distance between the upper set of equilibrium points (Fig. 18(a), A and B) and the separatrix that runs through the saddle point (D) is large enough that it is difficult to imagine a mechanism that would move shrub density into the lower equilibrium position. Although this argument is appropriate for this simplified caricature, the reality would not be as extreme. In particular, a persistent, rather than transient, large increase of H or decrease of G would lead to elimination of sensitive grasses and the movement of the G isocline to the left, perhaps to the point where the separatrix was crossed. Drought could produce the same result.

Settled peasant farmers, stock grazing

Those grazing areas managed by peasant farmers in southern Africa are now characterized by higher human density, fixed settlements, and intense and persistent (i.e. unvarying) grazing by cattle. This persistent and intense grazing results in areas with significant amounts of shrubs, little available grass, and a high density of emaciated cattle. Although such areas appear to be on the edge of collapse (e.g. Anon. 1920; West 1947, 1967; Allan 1965; Cleghorn 1966), they typically persist on that side of the separatrix where both grass and woody vegetation coexist.

These effects on the isoclines are suggested in Fig. 18(b). Under such prolonged, heavy grazing, the biomass of productive grasses is greatly reduced, water run-off is greater, and erosion leads to a decline in soil productivity. The result is that both r_G and r_W (the growth rates of grass and woody vegetation) are reduced, leading to a shift of both the grass and shrub isoclines to the left. Moreover, the demand for firewood can shift the shrub isocline even further left than that shown, potentially eliminating the lower equilibrium where shrubs can predominate.

Hence the reduced variability and the high intensity of grazing causes parameters of the system to evolve, producing a much less productive savanna, but one which still commonly persists at an upper equilibrium point. The biomass of ungrazeable grasses, G_0, is maintained at a high value as in the previous pattern, and the area on the G *v.* W graph which is occupied by the lower equilibrium could well be reduced. Although this system, like the previous one, is insensitive to large changes in value of H and G, productivity could decrease so much that it lowers human carrying capacity, leading to a human density too low to effectively reduce W. Drought would further contribute to such a collapse. Hence drought-induced disasters, even though uncommon, are more likely to occur than in the previous system.

Ranching, with fixed moderate stocking level

The types of grazing management on the larger commercial ranches feature either moderate but persistent levels of stocking, or seasonal rotational grazing and provision of drinking water supplies for cattle. Both the variability and intensity of grazing are considerably less than in the peasant farmer system. As a consequence, the balance of vegetation composition shifts towards highly productive sensitive grasses so that the land has higher rates of meat production than either of the two previous cases. Experienced range-managers note that the effects of sudden management changes, especially if coupled with a drought, can be far more devastating on a well-managed ranch than on areas which have been 'misused' for some time. It is a system of high productivity but one that is sensitive to change.

Figure 18(c) summarizes these effects on the zero-isoclines. That of woody vegetation is little affected but the grass zero-isocline shifts to the right because the rate of grass growth (r_G) is increased. More important, the ungrazeable grass refuge (G_0) is greatly reduced, as the sensitive grasses become dominant, so that grazing intensities that previously could be supported (without crossing the separatrix) no longer can be. Under reduced but persistent grazing, G_0 evolves to bring the separatrix close to the region in the G *v.* W graph which is occupied by the system. Hence small increases in stocking rate or in exogenous events (e.g. drought) that move the grass isocline leftward, can easily lead to the system moving to the lower equilibrium and a collapse of the productive cattle grazing system.

Mesquite-grass systems in southwestern U.S.A.

Prior to the high density of cattle stocking in the late 1800s, the ranges of the southwestern United States had very little, if any woody vegetation on the uplands. Mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*) was confined to drainage lines (Buffington & Herbel 1965). Subsequently, intense grazing by cattle resulted in invasion and predominance of mesquite in the uplands, with much less grass. Once grass had gone, an erosion pavement was formed that reduced infiltration of water into the soil, which, in turn, led to a high susceptibility to erosion (Glendenning 1952). Moreover, removal of cattle at this point was not followed by recovery of the range (Buffington & Herbel 1965).

Three conditions distinguish this system from those in south-eastern Africa. First, mesquite roots apparently do not have access to a reservoir of water that is unavailable to grass. Competition for water between grass and shrubs is therefore direct. Secondly, establishment of seedlings of mesquite is markedly curtailed by perennial grass cover. The number of summer-planted seeds required to produce one established seedling in the autumn is 16 times higher on grassed than ungrassed sites, and subsequent losses are 8 times higher (Glendenning 1952). Both these conditions would greatly depress the shrub zero-isocline at low W and high G (Fig. 18(d)). In addition, the direct competition for water between grass and mesquite would move the W zero-isocline to the right and the grass zero-isocline to the left when shrubs were abundant. Thirdly, seed dispersal of mesquite is greatly facilitated by cattle. High stocking levels result in increased rodent populations, and Glendenning & Paulsen (1955) have recorded the resulting increase in seed dispersal both by rodents (through lost caches) and cattle (by the spreading of seeds in dung). Although not shown in Fig. 19(d), this would result in the W zero-isocline shifting even further to the right as grazing intensity increased. The W zero-isocline shown in the figure represents that likely at intermediate to high grazing intensity.

These changes in isoclines result in only two stable equilibrium conditions–with either grass or mesquite predominating (Fig. 18(d)). Stable coexistence of both is not possible. So long as grazing is of moderate intensity, the range persists as a grassland. At a critical point however, further increase in grazing intensity leads to the vegetation moving towards dominance by mesquite. The grass sward does not recover if cattle are removed.

DISCUSSION

This analysis of semi-arid savanna grazing systems has largely concerned qualitative properties of stability. It was developed from knowledge of the existence of key processes and their qualitative form. The parameter values are so approximate that only a rough idea of magnitude is possible. Moreover, the model was confined to the dynamics of only two variables—grass and woody shrubs—under different levels of grazing. Other dynamic variables such as herbivore populations and the proportion of sensitive and of resistant grasses are likely to be important, but their dynamics were inferred rather than explicitly represented. Nevertheless, this simplified representation identifies some causes and interrelations between three important properties of ecological systems—productivity, resilience and variability. The relative values of these properties in the three grazing systems of southern Africa are summarized in Table 2.

The differences in herbivore productivity were inferred from movements of the grass zero-isocline only. The differences in resilience were inferred from the relationships between both the G and W zero-isoclines. Because the two estimates are based on different information, the relationship between productivity and resilience therefore need not be simple and direct. In this example, high resilience is associated with intermediate productivity.

These examples illuminate the concept of resilience. The original description by Holling (1973) contrasted resilience with the notion of local stability near an equilibrium. The latter emphasizes resistance to small disturbances, and rapid recovery from disturbance. Thus

TABLE 2. Summary of properties of grazing systems in southern Africa.

Grazing pattern	Resilience	Herbivore productivity	Variability in time
Nomadic and native ungulate grazing	High	Intermediate	High
Settled peasant farmers, stock grazing	Intermediate	Low	Intermediate
Ranching, fixed number of stock, and range management	Low	High	Low

local stability is associated with low variability. The notion of resilience emphasizes the existence of more than one domain of attraction (area bounded by the separatrix on the *G v. W* graphs) and the maintenance of that global structure through variability. In the present situation, reduction of variability changes competitive balances, so that parameters of the system change. Thus grass growth rate, r_G, decreases in the settled peasant farmer systems, primarily because of reduction in the biomass of sensitive grasses: the biomass of ungrazeable grass, G_0, decreases in constant stocking systems because of the reduction in biomass of resistant grasses.

Similar analyses of pest control and forest fires (Wright & Heinselman 1973; Ludwig, Jones & Holling 1978; Holling 1979) lead to the same conclusion. Insecticide spraying of spruce budworm in eastern Canada since 1950 has eliminated the boom-and-bust epidemic pattern, leaving more constant and moderate densities of budworm over larger areas. The result has been an accumulation of susceptible foliage over those same areas. Hence any relaxation of control would result in a more intensive and extensive outbreak than has ever been experienced. Effective control and suppression of fires in the national parks of the western United States reduced the incidence of fires but led to an accumulation of fuel and a more homogenous expanse of inflammable canopy. Again, any relaxation of control would result in costly consequences. In each case, reduced variability has led to the presumed parameters changing to produce a less resilient system. In the example of the fixed level of stocking on savanna (Fig. 18(c)), the ratio of sensitive to resistant perennial grasses shifts to favour the former as represented by decrease of the parameter G_0. In the budworm example, the spatial distribution of susceptible foliage becomes more homogenous. In the forest fire example, the physical structure of the forest shifts to allow continuity of fuel from the ground to, and through, the canopy. Each system becomes much more sensitive to errors in management and to exogenous events.

These examples suggest a more precise definition of resilience: resilience is the ability to adapt to change by exploiting instabilities, rather than the ability to absorb disturbance by returning to a steady state after being disturbed.

The four examples shown in Fig. 18 represent different combinations of parameters. The combinations were chosen to represent the particular parameter values that would evolve under grazing regimes that differed in the variability and intensity of grazing. There are two questions concerning resilience. The first is how to compare the resilience of the different grazing systems, given their parameters. The second is how to predict the direction and magnitude of parameter change, given the set of equations.

The earlier description of differences in resilience between three southern African examples related to the size of the upper area of stability on the *G v. W* graphs. But the descriptions were meaningful only in terms of kind and direction of disturbance. The important disturbances were increase in *H*, decrease in *G*, and leftward movement of the grass zero-isocline induced by drought. Because of these directions of disturbance, a convenient common reference point would be the lowest point in the set of upper equilibria (B, Fig. 18). One possible set of measures of resilience would be the distances in *H*, *G*, *W* space from the reference point to the separatrix. Since the separatrix is complicated to find, surrogates would be distances to the saddle point, D, through which the separatrix passes. Such resilience measures would decrease from (a) to (b) to (c) in Fig. 18.

The second aspect of resilience concerns the effects on parameters of controlling the variability and magnitude of variables (Peterman, Clark & Holling 1979). Many parameters of ecological models are, in reality, variables. They are chosen to be represented as constants (or perhaps as stochastic variables) because they are likely to change too slowly to be of interest (e.g. geomorphological changes), because of convenience and the need for simplification (e.g. herbivores in the model presented here) or because information or understanding of their behaviour is lacking. And yet the capability to adapt to disturbance is very much tied to the stability of key parameters and their tendencies to evolve under changed circumstances.

The general solution is not simply to expand the model to represent, where possible, parameters as variables. Such an expansion itself introduces additional parameters that are subject to the same uncertainty concerning their stability. If anything, the problem is magnified because the number of parameters increases rapidly as a model is expanded. An explicit effort to structure models as hierarchies can help to formalize the problem. That is, the problem can be structured as a hierarchy and defined by focusing on three or four levels of that hierarchy that differ in their speed or geographical scale or both. In the problem described here the speed of variables decreases from sensitive grasses to resistant grasses, to woody shrubs to herbivores. Events at levels below this hierarchy will operate so rapidly it might be assumed that an averaging effect allows their representation as parameters. Events at still higher levels might be presumed to operate so slowly that they can be represented as constants. Although this formalizes the problem, it does not resolve it since very fast variables can be eliminated by man's activity (e.g. soil microfauna important for maintaining soil fertility) and normally slow variables can be speeded up (e.g. hydrodynamic processes through irrigation).

At best we can suggest only a modest step. Whatever the choice of variables, explicit efforts can be made to infer the consequences on what was left out of the model. Often there is some information that can suggest the direction, if not the magnitude, of change of key parameters. That, in essence, was done in constructing the four examples of Fig. 18. Knowledge of the change in numbers of grazers and of the competition between the two kinds of grasses led to inferences about the way parameters would change under different grazing regimes, and that generated predictions of changes in productivity and resilience measures. It is then possible to design the key field experiments that can best test these qualitative predictions. Where these can be designed as part of management, additional information on economic and social feasibility can be produced.

In southern Africa one such key management experiment would be a pulsed grazing scheme within subsections of a typical ranch. Periods of intense over-grazing would alternate with periods of recovery of productive grasses, the latter accelerated by various experimental techniques. The timing of the grazing pulses would rotate among the subsections so that temporal variability for the ranch as a whole would be reduced by transforming it to spatial variability. Productivity (biological and economic) and resilience changes would be measured until they had stabilized. That would be followed by controlled application of different kinds and intensities of stress as a key test of the qualitative predictions discussed earlier. Similar tests, applied to areas managed with moderate fixed stocking strategies and to those subjected to intense grazing by stock kept by settled peasant farmers, would provide the necessary controls.

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2. VARIABLE DICTIONARY

AHEN - variable; total number of adult hens

AL - constant; the ratio of water uptake by shrubs to water uptake by grass

ANEST - variable; proportion of adult females which nest as a function of grass biomass

BE - constant; ratio of evaporation loss rate to water uptake rate by grass

C1 - constant; rate at which infiltration rate increases with increasing grass biomass (kg/ha)

C2 - constant; rate of consumption of grass biomass per unit of herbivore biomass (kg/kg)

CHICKS - variable; total number of chicks born

CPHEN - variable; number of chicks produced per nesting hen as a function of grass biomass

D4 - constant; grass biomass at which shrub growth rate from subsoil water is 50% of maximum (kg/ha)

DE - constant; ratio of evaporation loss rate to water uptake rate by shrubs

E - constant; evaporation loss rate (mm/year)

G - variable; grass biomass (kg/ha)

G0 - constant; grass biomass below which herbivore consumption does not occur (kg/ha)

GA - constant; the ratio of water uptake by grass to water uptake by shrubs

H - constant; herbivore biomass (kg/ha)

I0 - constant; minimum infiltration rate at low grass biomass levels

K - constant; proportional reduction in shrub growth rate from RS to S when grass biomass is high

LG - constant; the proportional rate of loss of grass from respiration and death (/year)

LW - constant; the proportional rate of loss of grass from respiration and death (/year)

MOD - variable; hen survival rate from shrub cover effects

NS - variable; variable which points to proper set of X and Y points to use in SLP interpolation

P - constant; inefficiency of subsoil water use by shrubs (kg/ha)

PCOVER - variable; percent shrub cover as a function of shrub biomass

PFEM - constant; proportion of population which is female

Q - the rate of grass consumption by herbivores (kg/ha/year)

RG - constant; grass growth rate due to topsoil water (kg/ha/year)

RS - constant; the increase in biomass of shrubs due to subsoil water when there is no grass biomass (kg/ha/year)

RW - constant; shrub growth rate from topsoil water (kg/ha/year)

S - variable; actual shrub growth rate from subsoil water (kg/ha/year)

SHEN - variable; hen survival rate as a function of grass biomass

SMALE - variable; male survival rate from shrub cover effects

TG - constant; grass water uptake rate (mm/year)

THN - variable; total hen population (yearlings plus adults)

TMALE - variable; total male population (yearlings plus adults)

TT - variable; total number of hens nesting

TW - constant; water uptake by shrubs (mm/year)

UG - variable; relative utilization of topsoil water by grass per unit of grass biomass (mm/kg)

UW - variable; relative utilization of topsoil water by shrubs per unit of shrub biomass (mm/kg)

W - variable; shrub biomass (kg/ha)

WHSUR - constant; hen winter survival

WMSUR - constant; male winter survival

XI - variable; infiltration rate (proportion of precipitation which enters soil when grass biomass is at maximum)

XJ - variable; X variable input into SLP function

XN - variable; number of interpolation points for SLP to be evaluated

XX(5,6) - constant; the array of X points for the SLP functions

YHEN - variable; total number of yearling hens

YNEST - variable; proportion of yearling females which nest as a function of grass biomass

YY(5,6) - constant; the array of Y points for the SLP functions

ZR - variable; normal random variate used to vary infiltration rate

Z Array Storage Variables

1 - XI
2 - UG
3 - Q
4 - G
5 - UW
6 - S
7 - W
8 - H
9 - AHEN
10 - AMALE
11 - TMALE
12 - THN

SLP Functions

(refer to first AEA Inc Saval Report for Figures)

1 - Adult nesting success vrs grass biomass (Fig. 6.6)
2 - yearling nesting success vrs grass biomass (Fig. 6.6)
3 - Chicks born per hen vrs grass biomass (Fig. 6.7)
4 - Hen survival vrs grass biomass (Fig. 6.8)
5 - Hen survival vrs percent cover (Fig. 6.9)
6 - Male survival vrs percent cover (Fig. 6.10)

3. PROGRAM LISTING

```
1  DIM Z(20,100),ZM(20)
10  FOR I = 1 TO 20:ZM(I) = 0: NEXT :NV = 20
11  IF  PEEK (104) <  > 64 THEN  POKE 104,64: POKE 103,1: POKE 16384,0: PRINT  CHR$ (4);"RUN SIMCON"
14  INPUT "SIM FROM ";A$: IF  LEFT$ (A$,2) = "GR" THEN 10100
15 ZS =  VAL ( LEFT$ (A$,2)):NT =  VAL ( RIGHT$ (A$,3))
16  IF NT < 1 THEN NT =  VAL ( RIGHT$ (A$,2))
18  FOR TIME = ZS TO NT
100  IF TI > 0 THEN 1000
110 H = 0:G = 200:LG = 1:G0 = 500
120 I0 = 0.1:TG = 0.21:TW = 0.122:RG = 4000
130 C1 = 600:C2 = 3.15:C3 = 0.0:E = 0
131 AL = TW / TG:BE = E / TG
135  DATA   0,0,.35,150,.8,500,0,0,0,0
136  DATA   0,0,.2,150,.65,500,0,0,0,0
138  DATA   0,0,1,100,5,500,0,0,0,0
140  DATA   .6,0,.6,100,.9,500,0,0,0,0
142  DATA   .25,0,.25,5,1,25,.5,50,.5,100
144  DATA   .35,0,.35,5,.65,15,.65,30,.5,50
146  FOR IN = 1 TO 6
147  FOR I = 1 TO 5: READ YY(I,IN),XX(I,IN): NEXT I
149  NEXT IN
150 WHSUR = .9:WMSUR = .8
152 AMALE = 100:AHEN = 100:YMALE = 100:YHEN = 100
153 PFEM = .6
200 W = 0
210 RW = 3000:RS = 4000:LW = 1:K = 1:D4 = 500:P = .1
220 GA = 1 / AL:DE = BE / AL
                                                   Equation #s in Walker et. al (1981)
998 W = 10:G = 1000
999  PRINT "ENTER COMMANDS,THEN CONT": END
1000 XI = (G + C1 * I0) / (G + C1) - - - - - - - - - - - - - - - (1)
1005  GOSUB 12000:XI = XI *  EXP (.25 * ZR)
1010 UG = 1 / (G + AL * W + BE) - - - - - - - - - - - - - - - - - (5)
1020 Q = (C2 * (1 - G0 / G)) / (G + C3): IF Q < 0 THEN Q = 0  - - - - - - (3)
1030 G = G + RG * XI * UG * G - LG * G - H * Q * G  - - - - - - - - - (4)
1040  IF G < 1E - 5 THEN G = 1E - 5
2000 UW = 1 / (W + GA * G + DE) - - - - - - - - - - - - - - - - - (9)
2010 S = RS * (1 - G / (K * (G + D4))) - - - - - - - - - - - - - - before (9) [unnumbered]
2020 W = W + W * RW * XI * UW + (S * W / (W + P)) - LW * W - - - - - - - (10)
2030 Z(5,TI) = UW:Z(6,TI) = S:Z(7,TI) = W
3000  REM     NESTING SUCCESS ADULTS
3010 XJ = G
3015 NSLP = 1
3020 XN = 3
3025  GOSUB 13000
3030 ANEST = SLP
3035  REM    NESTING SUCCESS YEARLINGS
3040 XJ = G
3045 NSLP = 2
3050 XN = 3
3055  GOSUB 13000
3057 YNEST = SLP
3060  REM     CHICKS PER HEN
3062 XJ = G:NSLP = 3:XN = 3
3063  GOSUB 13000
3065 CPHEN = SLP
3070  REM    # OF CHICKS
3078 TT = AN * AHEN + YN * YHEN:CH = CPHEN * TT * (1 - TT / 5000)
3080  REM     HEN SURVIVAL
```

```
3085 XJ = 6
3090 NSLP = 4
3095 XN = 3
3100  GOSUB 13000
3105 SHEN = SLP
3110  REM     MODIFY WITH COVER
3111 PCOVER = (W / 4000) * 100
3112  IF PCOVER > 100 THEN PCOVER = 100
3115 XJ = PCOVER
3120 NSLP = 5
3125 XN = 4
3130  GOSUB 13000
3135 MOD = SLP
3140  REM    MALE SURVIVAL
3145 XJ = PCOVER
3150 XN = 5
3155 NSLP = 6
3160  GOSUB 13000
3165 SMALE = SLP
3170 AHEN = (AHEN + YHEN) * SHEN * MOD
3175 AMALE = (AMALE + YMALE) * SMALE
3180 YHEN = CHICKS * PFEM
3185 YMALE = CHICKS * (1 - PFEM)
3190  REM    ADD IN WINTER MORTALITY
3195 AHEN = AHEN * WHSUR
3200 AMALE = AMALE * WMSUR
3205 YHEN = YHEN * WHSUR
3210 YMALE = YMALE * WMSUR
3215 THN = AHEN + YHEN:TMALE = AMALE + YMALE
3220  PRINT
3300  PRINT "AN=";AN,"YN="YN
3310  PRINT "CP=";CP,"SH=";SH
3315  PRINT "PC=";PC,"MOD=";MOD
3320  PRINT "SM=";SM
5000 Z(1,TI) = XI:Z(2,TI) = UG:Z(3,TI) = Q:Z(4,TI) = G
5005 Z(8,TI) = H
5006 Z(9,TI) = AHEN:Z(10,TI) = AMALE:Z(11,TI) = TMALE:Z(12,TI) = THN
10000  FOR J = 1 TO NV
```

III. WATVEG

I. INTRODUCTION

This model is a simplified version of the hydrology and vegetation submodels described in Sonntag et al. (1982) and the first section of this report.

The model considers only one range site on one acre of a pasture. However, the time step is flexible; it is determined by setting the variable ND (e.g., 7 for a weekly time step). The basic structure of the model is as follows.

Changes in soil moisture in two soil layers (0 - 20", 20 - 40") are computed based on precipitation, infiltration and evapotranspiration. The actual above ground biomass and potential above ground biomass stored in roots are modelled for both grasses and shrubs. Grasses draw water only from the top soil layer; shrubs draw water from whichever soil layer has more water. Growth rates of vegetation depend on soil moisture levels, a phenology/temperature factor, the vegetation type (grasses or shrubs), a competition factor, and translocation between above and below ground biomass.

Cattle grazing can be set to occur in any period of one week or longer; the user sets the number of acres per cow, and the estimated weekly biomass of forage consumed per cow.

2. VARIABLE DICTIONARY

AB(2)	actual biomass of grasses & shrubs (green and non-green)
AC	# acres/cow
ANS	temporary variable (for growth rate)
AW	available water capacity ("/")
B2	green biomass "mortality" when RG = 0.0
BC(2)	base cover (% cover with zero biomass of grass & shrubs respectively)
BG	fraction bare ground (e.g. 0.2)
CC	cattle consumption (lbs/week/cow)
DD(2)	death rate/week of grasses and shrubs
DP(2)	depths of 2 soil layers
DS	week of seed set
EF	growth reduction factor for competition for water
ET	actual evapotranspiration/week (")
FD	week of flowering
GB(2)	above ground green biomass (lb/acre) of grasses (1) & shrubs
IW	week # in year
KB(2)	half saturation constant for % cover relationship
KQ	half saturation constant for soil moist.→ plant growth equation
MB(2)	maximum biomass (100% cover)
MR(2)	reduction in growth rate due to moisture
MX(2)	maximum growth/week of grasses & shrubs respectively
ND	# days/timestep
NE	necessary evapotranspiration (in/week per lb/a of biomass)
NQ	equation # (pointer)

OG(2)	old green biomass
PC(3)	% cover of grasses; shrubs (grasses & shrubs) respectively
PF	phenology/temperature factor
PW	total potential water transpiration
R	random number
RD	radiation (langleys)
RG	real growth rate of plant
RO	runoff (inches)
RQ	r parameter for soil moisture → plant growth equation
RR	Pr (no rain)
RS(2)	translocation from root to shoot (fraction of root storage/week)
RT(2)	root biomass (lb/a) (potential above ground green biomass)
S	actual retention parameter
S2	slope of mortality-growth line
SM	maximum retention parameter
SO(2)	% soil moisture by layer
SR(2)	translocation from shoot to root (fraction of above ground green biomass/week
SS(1)	saturation parameter for soil moisture → plant growth equation
TB	total above ground biomass
TE	temperature (°F)
TI	time (# weeks)
TP	cumulative precipitation
WD(2)	water density in wettest of two layers ("/")
WI	total infiltration
WN	potential evapotranspiration

WT(2)	water transpired from each soil layer (")
WW(2)	amount of water in each soil layer (")
XX	temporary variable for soil moisture

3. PROGRAM LISTING

105 - 199	Initialization.
210 - 240	Compute temperature and radiation from sin curves
270	Compute potential evapotranspiration
300	Allocate potential evapotranspiration to each soil layer, accounting for % runoff and % green
320	Choose wettest layer for shrubs
330	Compute water transpired from soil layer if layer filled to AWC (water not limiting)
350 - 430	Take water out of soil
470 - 530	Compute rainfall (sin curve for probability of no rain; random number for actual rain)
550 - 590	Compute curve numbers, retention parameter
600 - 710	Fill up water layers with infiltration
1000 - 1020	Compute phenology/temperature factor
1040 - 1210	Compute soil moisture constraint (using logistic equation)
1260 - 1300	Compute evapotranspiration limitation on growth
1310 - 1320	Compute real growth rate of plant
1330 - 1360	Death rate (proportional to phenology factor if early spring or late fall)
1370 - 1380	Growth and death of green biomass
1384	Cow grazing
1390 - 1430	Translocation (root storage after flowering removes green biomass but not total biomass)
1440 - 1560	Compute % cover based on biomass

```
1  DIM Z(30,52),ZM(30)
2  DIM SD(2),MR(2),MX(2),SS(1),RQ(1),KQ(1),GB(2),RT(2),OG(2),RG(2),KB(2),DP(2),WW(2),WU(2),WT(2),RS(2),SR(2),BC(2),DD(2),S2(2)
10  FOR I = 1 TO 30:ZM(I) = 0: NEXT :NV = 30
11  IF  PEEK (104) <  > 64 THEN  POKE 104,64: POKE 103,1: POKE 16384,0: PRINT  CHR$ (4);"RUN SIMCON"
12  PRINT "ENTER COMMANDS,THEN CONT": END
14  INPUT "SIM FROM ";A$: IF  LEFT$ (A$,2) = "GR" THEN 10100
15 ZS =  VAL ( LEFT$ (A$,2)):NT =  VAL ( RIGHT$ (A$,3))
16  IF NT < 1 THEN NT =  VAL ( RIGHT$ (A$,2))
18  FOR TIME = ZS TO NT
100  IF TI > 0 THEN  GOTO 200
105  REM    INITIAL CONDITIONS
107 AW = 0.14
110 DP(1) = 20:DP(2) = 20
115 WW(1) = DP(1) * AW * 0.75
117 WW(2) = DP(2) * AW * 0.25
120 R =  RND ( - 1)
125 TP = 0
126 CC = 200
127 AC = 20
128 PF = 1
130 SS(1) = 1
135 RQ(1) = 0.8
140 KQ(1) = 15.
145 MX(1) = 1.2
146 GS = 23
147 GF = 26
150 MX(2) = 0.6
151 RS(1) =  - 0.1:RS(2) =  - 0.1
152 SR(1) = 0.05:SR(2) = 0.05
155 IW = 0
160 NE = 0.01
161 BC(1) = 0.1:BC(2) = 0.1
162 KB(1) = 1000:KB(2) = 1000.
163 BG = 0.2
165 B2 = 0.10
170 S2(1) = 0.07:S2(2) = 0.07
172 PI = 3.14159:ND = 7
175 FD = 26
177 B3 = 0.1 * FD / (FD - 8)
178 S3 = B3 / FD
190 GB(1) = 50.:AB(1) = 50
195 GB(2) = 50.:AB(1) = 50
197 RT(1) = 200.
198 RT(2) = 200.
199  PRINT "ANY CHANGES? THEN CONT": END
200 IW = IW + 1
205  IF IW * (ND / 7) > 52 THEN IW = 0
207  IF IW = 0 THEN TP = 0:CR = 0
210  REM    TEMPERATURE**********
220 TE = 10 + 60 *  SIN ((IW * (ND / 7) / 52) * PI)
240  REM    RADIATION ***********
250 RD = 200 + 600 *  SIN ((IW * (ND / 7) / 52) * PI)
260  REM    POTENTIAL ET ********
270 WU = ND * (0.014 * TE - 0.37) * RD / 580.
280  IF WU < 0 THEN WU = 0
285 PW = WU
290  FOR I = 1 TO 2
300 WT(I) = WU * 0.4 * PF * PC(I)
```

```
310 WD = WW(1) / DP(1)
320  IF I = 2 AND (  (2) / DP(2)) >  = WD THEN WD = WW(2) / DP(2)
330 WT(1) = WT(1) + PF * WD / AW
340  NEXT
350 WU = WT(1) + WT(2)
360 ET = 0
370  IF WT(1) < WW(1) THEN  GOTO 390
375 ET = ET + WW(1)
380 WW(1) = 0
385  GOTO 400
390 WW(1) = WW(1) - WT(1):ET = ET + WT(1)
400 WX = 2: IF WW(1) > WW(2) THEN WX = 1
410  IF WT(2) < WW(WX) THEN  GOTO 430
415 ET = ET + WW(WX):WW(WX) = 0
425  GOTO 460
430 WW(WX) = WW(WX) - WT(2):ET = ET + WT(2)
460  PRINT "      ********"
461  PRINT "WEEK ";IW * (ND / 7);" TE=";TE;" RD=";RD
462  PRINT "  AFTER EVAPOTRANSPIRATION:"
463  PRINT "WW(1)=";WW(1);" WW(2)=";WW(2): PRINT "WT(1)=";WT(1);" WT(2)=";WT(2): PRINT "PW=";PW
470 R =  RND (1)
480 RR =  SIN ((IW * (ND / 7) / 52) * PI) * 0.72
490  IF R < RR THEN RN = 0: GOTO 550
520 RN = ( RND (1) * 0.5 + 0.5) * (ND / 7)
530 TP = TP + RN
550 CN = 87 - 0.18 * PC(3)
560 SM = (1000. / CN) - 10.
570 S = SM * (AW - (WW(1) + WW(2)) / (DP(1) + DP(2))) / AW
575 RO = 0
580  IF RN > 0.2 * S THEN RO = ((RN - 0.2 * S) ^ 2) / (RN + 0.8 * S)
590  IF RN < (0.2 * S) THEN RO = 0.
595 CR = CR + RO
600  REM    INFILTRATION ********
610 WI = RN - RO
630  IF WI < 0. THEN WI = 0.
635 NF = WI
640  FOR I = 1 TO 2
650  IF (WI + WW(I)) < (DP(I) * AW) GOTO 690
660 WI = WI - (DP(I) * AW - WW(I))
670 WW(I) = DP(I) * AW
680  GOTO 710
690 WW(I) = WW(I) + WI
700  GOTO 720
710  NEXT I
720  PRINT "  AFTER INFILTRATION:": PRINT "WW(1)=";WW(1);" WW(2)=";WW(2): PRINT "RN=";RN
740 TB = GB(1) + GB(2)
1000  REM    PHENOLGY & TEMP. ****
1020 PF =  SIN (IW * (ND / 7) / 52 * PI)
1040  REM    SOIL MOISTURE CONSTRAINT ***
1050 TB = GB(1) + GB(2)
1060  FOR I = 1 TO 2
1080 SO(I) = ((WW(I) / DP(I)) / AW) * 100.
1090 NQ = 1
1100 XX = SO(1)
1110  IF I = 2 AND SO(2) > SO(1) THEN XX = SO(2)
1180  GOSUB 1690
1200 MR(I) = ANS
1210  IF MR(I) > 1 THEN MR(I) = 1
1240  REM    EVAPOTRANSPIRATION ****
1260 EF = (ET / TB) / (NE * (ND / 7))
1280  IF EF > 1.0 THEN EF = 1.0
1300  IF EF < 0.0 THEN EF = 0.0
1310 RG(I) = MX(1) * PF * MR(I) * EF
1315  IF IW * (ND / 7) < 8 THEN RG(I) = 0.
1320  IF IW * (ND / 7) > 40 THEN RG(1) = 0
1330  REM     MORTALITY *******
```

```
1335 DD(I) = 0
1340  IF IW * (ND / 7) < 8 OR IW > FD THEN DD(I) = B2 - S2(I) * PF
1360  IF DD(I) < 0. THEN DD(I) = 0.
1370 OG(I) = GB(I)
1380 GB(I) = GB(I) * (ND / 7) * (RG(I) + 1. - DD(I)):AB(I) = AB(I) * (ND / 7) * (RG(I) + 1 - DD(I))
1382  REM  COW EATS****
1384  IF IW * (ND / 7) > GS AND IW * (ND / 7) < GF AND I = 1 THEN GB(1) = GB(1) - CC * (ND / 7) / AC:AB(1) = AB(1) - CC * (ND / 7) /
 AC
1390  REM    TRANSLOCATION ****
1392 RS(I) = B3 - S3 * IW * (ND / 7)
1395 DR = 0
1400  IF IW * (ND / 7) < FD AND IW * (ND / 7) > 8 THEN DR = RS(I) * RT(I):GB(I) = GB(I) + DR:AB(I) = AB(I) + DR
1410  IF IW * (ND / 7) > FD AND IW < 40 THEN DR =  - SR(I) * GB(I):GB(I) = GB(I) + DR
1430 RT(I) = RT(I) - DR
1440  NEXT
1450  REM    % COVER *****
1520  FOR I = 1 TO 2
1530 PC(I) = (AB(I) * (1. - BC(I) - BG)) / (KB(I) + AB(I)) + BC(I)
1540  IF PC(I) > 1 THEN PC(I) = 1.0
1550  NEXT I
1555 PC(3) = PC(1) + PC(2)
1560  IF PC(3) > 1 THEN PC(1) = PC(1) / PC(3):PC(2) = PC(2) / PC(3):PC(3) = PC(1) + PC(2)
1565 Z(21,TI) = AB(1)
1567 Z(22,TI) = AB(2)
1569 Z(23,TI) = ET
1571 Z(24,TI) = RD
1573 Z(25,TI) = CR
1580 Z(1,TI) = GB(1)
1590 Z(2,TI) = GB(2)
1600 Z(3,TI) = SO(1)
1610 Z(4,TI) = SD(2)
1620 Z(5,TI) = RN
1630 Z(6,TI) = PC(1)
1640 Z(7,TI) = PC(2)
1650 Z(8,TI) = PF
1660 Z(9,TI) = RT(1)
1670 Z(10,TI) = RT(2)
1671 Z(11,TI) = RS(1)
1672 Z(12,TI) = RS(2)
1673 Z(13,TI) = TP
1674 Z(14,TI) = RG(1)
1675 Z(15,TI) = RG(2)
1676 Z(16,TI) = RO
1677 Z(17,TI) = NF
1678 Z(18,TI) = WT(1)
1679 Z(20,TI) = MR(1)
1680  GOTO 2000
1689  REM  LOG ISTICEQN *  *  *  *  *
1690 ANS = SS(NQ) / (1.0 +  EXP (RQ(NQ) * (KQ(NQ) - XX)))
1700  RETURN
2000  REM    ***END***
10000  FOR J = 1 TO NV
```

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